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MATERIALS OF CONSTRUCTION

THEIR MANUFACTURE, PROPERTIES, AND USES

BY

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PREFACE

THIS work is an outgrowth of certain lectures and notes which have been used in the author's classes in the College of Civil Engineering, Cornell University, for the past several years. Its preparation was undertaken to meet the need which was felt for a general text-book covering the manufacture, properties, and uses of the more common materials of engineering construction in a comparatively concise and thoroughly modern manner.

Although this book is intended primarily for use as a text-book of somewhat elementary character and is not a treatise exhaustively covering the very broad field of " Materials of Construction," the treatment has been made more detailed in some respects than may be necessary for class-room purposes, and its applications as a general reference work thereby broadened.

The treatment of the various classes of materials considered follows a general systematic form which has been made uniform throughout so far as has been found practicable. The consideration of each material or class of materials is prefaced by a discussion of its ordinary applications in engineering construction, followed by a study of its manufacture or natural occurrence, and concluded by a discussion of physical and mechanical properties in their relation to its uses.

As a result of the author's experience in the teaching of this subject, the properties exhibited by a given material are, for the most part, considered as dependent phenomena closely related to certain more or less variable factors connected with the process of manufacture, natural occurrence, and conditions of service or testing, and not as independent qualities inherent in that material. It has been considered advisable to avoid the inclusion of tabulations of investigational data whenever the data could be presented graphically by curves or diagrams; discussions of conflicting empirical data on points admitting of controversy have been reduced to a minimum; and an effort has been made to present the material in a definite, concrete form, the necessity for the exercise of discriminative judgment upon the part of the student being obviated by conclusions drawn by the author, even though it is recognized that in so doing errors of judgment may be made, and the criticism of those who object to any form of dogmatic statement is invited.

The subject of testing materials has not been covered, except in so far as methods of testing are inseparable from discussions of the properties of materials revealed by laboratory tests. It is the author's conviction that this subject can be handled only in the laboratory itself, and the place for such material is therefore in a laboratory manual. It is assumed, however, that a laboratory course in testing materials will invariably parallel and supplement the text-book course in the study of materials.

The author cannot make a pretense of being a specialist in all of the fields which are covered in the various chapters of this book, and this work is therefore to a very large degree a compilation of data and opinion from a great many different sources. The author takes pleasure in acknowledging his great indebtedness to the large number of engineers and manufacturers who have privately or by their writings contributed much to make up this volume. A large number of technical books which are devoted to the consideration of some part of the ground covered by this text have been frequently consulted and freely used. An effort has been made to always acknowledge the source of information so obtained, and if any error of omission has been committed in this respect, it has been committed inadvertently, not by intention.

The following well-known text-books and reference works have been most frequently used:

" Cements, Limes, and Plasters," by E. C. Eckel; " Portland Cement," by R. K. Meade; " Manufacture of Portland Cement," by R. C. H. West; " Masonry Construction," by I. O. Baker; " Stone for Building and Decoration," by G. P. Merrill; " Building Stones and Clay Products " and " Economic Geology," by Heinrich Ries; " The Blast Furnace and the Manufacture of Pig Iron," by Robert Forsythe; " The Metallurgy of Iron and Steel," by Bradley Stoughton; " The Metallurgy of Steel " and " Iron, Steel, and Other Alloys," by H. M. Howe; " The Manufacture and Properties of Iron and Steel," by H. H. Campbell; " Iron and Steel," by H. P. Tiemann; " Modern Iron Foundry Practice," by G. R. Bale; " Cast Iron," by W. J. Keep; " The Production of Malleable Castings," by Richard Moldenke; " The Corrosion and Preservation of Iron and Steel," by A. S. Cushman and H. A. Gardner; " The Metallography of Iron and Steel," by Albert Sauveur; and " Economic Woods of the United States " and " The Mechanical Properties of Wood," by S. J. Record.

The following periodicals and publications of various societies have also been frequently consulted:

"Engineering News," "Engineering Record," "Metallurgical and Chemical Engineering," Proceedings of the American Society for Testing Materials, Proceedings of the International Association for Testing Materials, Transactions of the American Society of Civil Engineers, Proceedings of the Institution of Mechanical Engineers, Journal of the Iron and Steel Institute, "Tests of Metals," published annually by the U. S. War Department, "Mineral Resources," published annually by the U. S. Geological Survey, Reports of the various State Geological Surveys, the publications of the Forestry Division of the U. S. Department of Agriculture, and the publications of the U. S. Bureau of Standards.

ADELBERT P. MILLS.

ITHACA, N. Y.
February 20, 1915.

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THE MATERIALS OF MASONRY CONSTRUCTION

CEMENTING MATERIALS

CHAPTER I

GYPSUM PLASTERS

GENERAL

1. Definition and Classification. Gypsum plasters comprise all that class of plastering and cementing materials obtained by the partial or complete dehydration of relatively pure or impure natural gypsum, and to which certain materials which serve as retarders or hardeners, or which impart greater plasticity to the product, may or may not have been added during or after calcination. The usual classification of gypsum plasters follows:

CLASSIFICATION OF PLASTERS *

(a) Produced by the incomplete dehydration of gypsum, the calcination being carried on at a temperature not exceeding 190° C.

(1) *Plaster of Paris*, produced by the calcination of a pure gypsum, no foreign materials being added either during or after calcination.

(2) *Cement Plaster* (often called *Patent* or *Hard Wall Plaster*), produced by the calcination of a gypsum containing certain natural

---

* Eckel, " Cements, Limes, and Plasters."

impurities, or by the addition to a calcined pure gypsum of certain materials which serve to retard the set or render more plastic the product.

(b) Produced by the complete dehydration of gypsum, the calcination being carried on at temperatures exceeding 190° C.

(3) *Flooring Plaster*, produced by the calcination of a pure gypsum.

(4) *Hard Finish Plaster*, produced by the calcination at a red heat or over, of gypsum to which certain substances (usually alum or borax) have been added.

2. Application in the Arts and Industries. Raw gypsum, ground but not calcined, is used extensively as a soil amendment and as a slight necessary adulterant to retard the setting of Portland and natural cements. It is also used as an ingredient of some oil paints, many water paints, wall tints and calcimines, in some dry colors and crayons, and in imitation ivory, meerschaum, etc. A pure white even-grained variety called alabaster is considerably used for sculptural decorations, art work, etc.

Calcined plasters are used as a retarder in cements, as a casting plaster for stereotype molds, pottery, rubber stamps, etc., as dental plaster, as a cement to bed plate glass during grinding, as an ingredient of many patented cements, and as a seal or cement used in the construction of innumerable small instruments, electric fittings, etc.

3. Structural Uses. Gypsum plasters of one variety or another are used structurally as interior wall plasters, both for mortar and hard-finish coats, as stucco wall coverings and architectural ornamentation of exteriors, as molded hollow blocks and tiles for interior partition walls, as plaster-board wall covering (laminated with thin sheets of cardboard or wood), for flooring plasters, and for numerous minor structural purposes.

MANUFACTURE OF GYPSUM PLASTERS

4. Gypsum Rocks. Pure gypsum is a hydrous lime sulphate ($CaSO_4+2H_2O$), the composition of which by weight is:

Lime Sulphate ($CaSO_4$)	Lime (CaO)	32.6%	79.1%
	Sulphur trioxide (SO_3)	46.5	
Water (H_2O)			20.9
			100 0%

Natural deposits of gypsum are practically never pure, however, the lime sulphate being adulterated with silica, alumina, iron oxide, calcium carbonate, and magnesium carbonate. The total of all impurities amounts to from a few tenths of 1 per cent up to a maximum of 5 or 6 per cent.

The physical form of a natural gypsum is usually that of a *massive* rock formation. It does occur also as an *earthy gypsum* or *gypsite*, and as *gypsum sands* in some localities in the southwestern part of the United States. *Alabaster* is a specially pure white massive gypsum of very even texture and fine grain, and *selenite* is a white semi-transparent crystalline gypsum which occurs only in relatively small deposits in massive gypsum.

5. Theory of Calcination. If pure gypsum be subjected to any temperature exceeding 100° C. by more than a very slight amount, but not exceeding 190° C., a certain portion of the water of combination is driven off. This portion is definitely fixed at three-fourths of that originally present, i.e., 1½ molecules, providing that the heating be continued for a sufficient period of time to accomplish the ultimate extent of dehydration possible without heating above 190° C. The resultant product is called *Plaster of Paris* ($CaSO_4+1/2H_2O$). Since the time required for the process is directly dependent upon the temperature maintained, it is the quite universal practice to maintain this temperature near the highest possible limit, thus effecting an economy in both time and fuel. Thus it happens that plaster of Paris and cement or hard wall plasters are rarely calcined at temperatures outside the limits 140° to 180° C. Plaster of Paris readily recombines with water to form gypsum, hardening in a very few minutes.

If the gypsum be calcined at temperatures much above 190° C. it loses all of its water of combination, becoming an anhydrous sulphate of lime ($CaSO_4$). All temperatures exceeding that required for complete dehydration result in some impairment, temporary or permanent, of the capacity of the plaster for recombination with water, the extent of the injury being dependent upon the intensity and the time-extent of the heating and upon the state of subdivision of the material. It is not at all difficult to render the plaster totally incapable of recombining with water (dead-burnt plaster), the product being valueless as a cementing material. If, however, the material is calcined in a lumpy condition the temperature not exceeding 400° to 500° C., and not prolonged beyond three or four hours, the principal effect upon the products is a great retardation of the rate of setting and hardening, an hydrate being ultimately formed, in the course of days or weeks, instead of minutes, which greatly exceeds ordinary plaster in hardness and strength. These principles govern the manufacture of flooring plasters and hard-finish plasters, though there are differences in the methods employed in producing these two varieties of hard-burned plasters which will be later noted.

6. Practice of Calcination. Plaster of Paris and cement or hard wall plasters are made in a practically identical manner, the distinct properties of the two materials being due to the use of pure gypsum in the one case, and impure gypsum or adulterated pure gypsum in the other.

Two operations only are involved in the process of manufacture: crushing and grinding, and calcination. Three-fourths of the plaster plants in the United States use gypsum rock alone, about one-sixth of the plants use earthy gypsum or gypsite, and the balance use both rock and earthy gypsum. Rock gypsum is first crushed in a gyratory * or jaw * crusher to fragments about 1 inch in diameter. Intermediate reduction to about the size of peas is accomplished in a pot * crusher or cracker,* and final pulverization in a buhr-mill,* a rock-emery mill,* or other type of finishing mill. Gypsite requires no preliminary crushing, but is handled by the finishing mill alone, and material destined to be calcined in a rotary cylinder calciner is not pulverized until after calcination.

Ninety-five per cent of the plaster made in the United States is calcined in kettles of the general type of that shown in Fig. 1. The kettle is a cylindrical steel vessel, 8 to 10 feet in diameter and 6 to 9 feet high, mounted upon a masonry foundation. The bottom is convex, rising about 1 foot in the center, and made of cast iron. A masonry wall encloses the steel cylinder, leaving an open annular space between for the circulation of heat. A fire is maintained on grates below the kettle, and the heated gases pass through ports into the open annular space, then in horizontal flues through the kettle and out through the stack. A central vertical shaft propels paddles just above the bottom, thus keeping the material agitated and preventing the burning out of the bottom.

The charge, consisting of 7 to 10 tons of ground gypsum, is delivered by a chute to the charging door provided in the sheet-iron cap of the kettle. Heat is gradually applied as the charge is slowly fed in and, as the temperature rises after charging is complete, the contents boil violently until the mechanically held water is driven off. Boiling is renewed again when the water of combination begins to be driven off, and continues until the end of the process. The maximum temperature attained in a period of two to three hours does not usually exceed 190° C. (It may be considerably higher in the case of the less pure earthy gypsum.) The point at which the process is complete is sometimes determined by careful observation of temperatures throughout, but is often a matter of judgment upon the part of an experienced calciner. The kettle is discharged by blowing out through a small gate in the lower part of the side of the shell. The hot material runs like water into a masonry pit provided for the purpose and, after cooling therein, is elevated to screens

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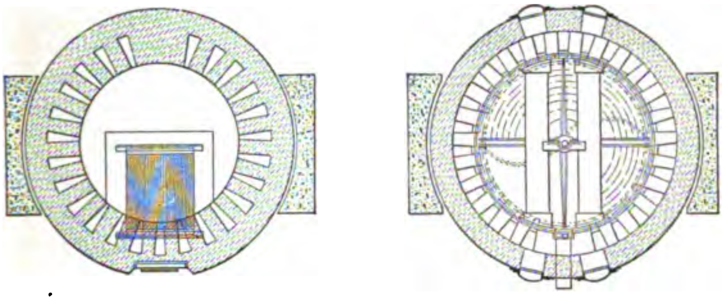
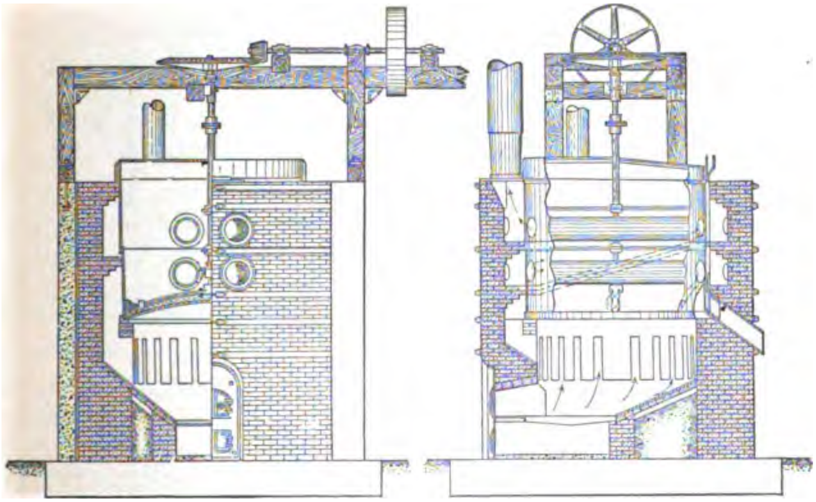
* These various types of crushing and grinding machinery are described and illustrated on pages 119 to 122 incl. of this volume.

which remove a small percentage of over-size material which must be ground.

The rotary cylinder type of calciner, Fig. 2, is a late development in the plaster industry, but is doubtless destined to replace the less economical kettle. When the rotary calciner is employed the raw material is used in the condition in which it comes from the cracker, and feeding from the supply bin is continuous. The cylinder is set on a slight incline, and the lumpy material fed in at the upper end gradually traverses its length as the cylinder slowly rotates, is discharged at the lower end, and enters calcining bins which are lined with non-absorptive paving



Horizontal Sections.



Vertical Sections.

Fig. 1.—Four Flue Plaster Calcining Kettle.

brick, and from which outside air is excluded. The cylinder is enclosed within a brick chamber which includes a firebox at one end, and a considerable air space is provided between the steel shell and the masonry. The hot furnace gases are drawn into the brick chamber by a fan and there mixed with sufficient air, admitted from the outside, to secure the desired temperature. These gases are drawn into the cylinder through hooded openings provided at intervals, and pass through it in a reverse direction to that taken by the wet material. A dust chamber provided between the cylinder and the stack catches the most finely ground plaster which has been carried off in suspension by the gases.

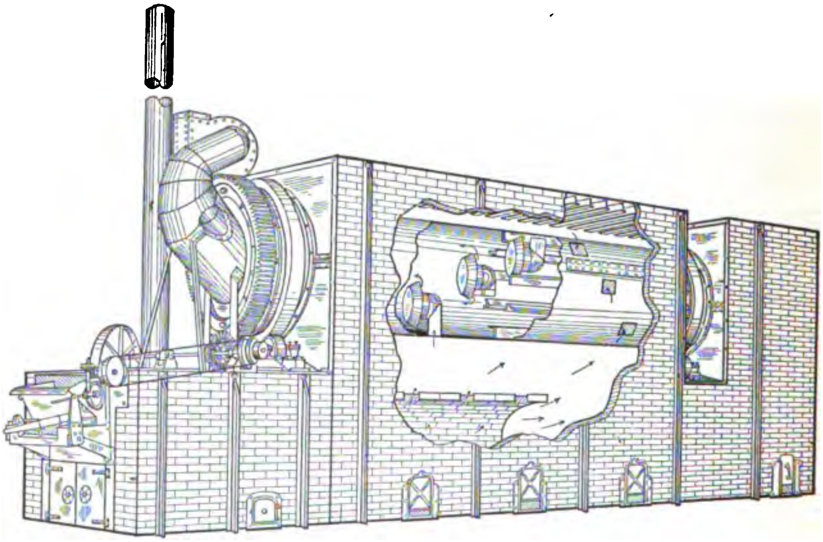


FIG. 2.—Rotary Cylinder Type of Plaster Calciner.

The heat attained in the rotary calciner is from 200° to 300° C., but time does not suffice for the complete dehydration of the gypsum, and the removal of combined water is completed in the calcining bins through the agency of the residual heat of the material itself. After about thirty-six hours the process will have been completed. Air inlets are then opened and the contents of the bin are rapidly cooled. By providing four bins for each calciner the process is made to be continuous; while one bin is being charged, the process of calcination is being completed in the second and third bins, and the fourth is being discharged. The product of the calcining bins is conveyed to finishing mills and there pulverized to the form of the marketable article.

Many cement or hard wall plasters are made direct from earthy gypsum or gypsite, which is often found to contain a suitable percentage of foreign material of such character that no corrective material need be added either to retard the set or impart plasticity.

Flooring plaster is produced by the calcination of a pure gypsum in a lump form in a vertical separate-feed kiln which differs little from the separate-feed kiln used for the calcination of lime.* The fuel, burned on grates outside the kiln, does not come in contact with the gypsum, but the hot gaseous products of combustion pass directly through it, heating it to a temperature of from 400° to 500° C. Higher temperatures, or prolongation of heating beyond three or four hours, ruin the plaster by robbing it of its setting properties as above noted. Fine pulverization of the plaster must follow calcination.

The best-known variety of hard-finish plaster is the so-called *Keene's cement.* This plaster is produced by the double calcination of a very pure gypsum at a red heat, alum being added between the two burnings. The kiln used resembles very closely the mixed-feed lime kiln hereinafter described.† After the lump gypsum has been calcined at a red heat, the resulting anhydrous lime sulphate is immersed in a 10 per cent alum solution, then recalcined, and finally pulverized in a finishing mill.

7. Additions Subsequent to Calcination. Plaster of Paris is never adulterated in any way during manufacture, but cement or hard wall plasters often require the addition of a retarder to render them sufficiently slow setting to adapt them to structural use. The retarders commonly used are unconsolidated organic materials, such as glue, sawdust, blood, packing-house tankage, etc. As a rule the amount of retarder required does not exceed 0.1 to 0.2 per cent. Certain very impure gypsums produce a plaster which is too slow setting, or sometimes, as in the case of dental plaster, extreme rapidity of set is required. In such instances the addition of an accelerator is necessary. The materials used for this purpose are crystalline salts, common salt (NaCl) being one of the best.

Gypsum plasters destined for use as wall plasters must usually have their plasticity enhanced by the addition of some material such as clay or hydrated lime, through the agency of which the naturally "short," non-plastic material is greatly improved in working qualities and sand-carrying capacity. With the exception of those plasters which are made from earthy gypsum and which naturally contain 20 per cent or more of clay, it is therefore the usual practice to add about 15 per cent of hydrated lime or, less frequently, clay, to the calcined plaster. Greater cohesiveness is also usually imparted to wall plasters by the addition

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* See Fig. 12.

† See Fig. 11.

of finely picked hair or shredded wood fiber. Not more than 1½ to 3 pounds of hair or 75 to 150 pounds of wood fiber per ton of calcined plaster is required.

No additions are made to flooring plaster subsequent to calcination. Keene's cement is treated with an alum bath as above noted. Mack's cement, another variety of hard-finish plaster, is made by the addition to dehydrated gypsum (flooring plaster) of 0.4 per cent of calcined sodium sulphate (Na_2SO_4), or potassium sulphate (K_2SO_4).

PROPERTIES AND USES OF GYPSUM PLASTERS

8. Setting and Hardening.* **Action of Accelerators and Retarders.** The setting of plaster of Paris and other gypsum plasters is a simple process of recombination of the partially or totally dehydrated lime sulphate with water to reform hydrated lime sulphate or gypsum. A pure plaster of Paris sets in from five to fifteen minutes after the addition of water. Plasters made from impure gypsum are less quick setting, requiring from one to two hours, and the completely dehydrated classes of plasters are slow setting, whether adulterated or not, because of the action of high temperatures in retarding the rate of setting. The ultimate degree of hardness attained by impure cement or hard wall plasters greatly exceeds that of pure plaster of Paris, and the hard-burned plasters are hardest of all.

The action of accelerators and retarders, according to Dr. Grimsley,† is based upon the asserted fact that crystalline growth cannot occur unless there are present some crystals which have escaped dehydration during burning, and which act as promoters of hydration, inducing neighboring molecules of lime sulphate to assume the crystalline form by the taking up of water of crystallization. The theory further involves the acceptance of the hypothesis that the progressive hardening and gain in strength is due to the formation of a mass of interlocking crystals. The action of accelerators and retarders is therefore explained by assuming that "any substance (added to the water with which the calcined plaster is mixed or to the dry plaster) which will keep the molecules apart or from too close contact will retard the setting. Such substances are dirt or organic matter that is not of a crystalline character." On the other hand, mineral salts induce crystallization because of their crystalline character.

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* By the term "setting" we mean the initial loss of plasticity, while "hardening" means the subsequent gain in ability to resist indentation or abrasion which accompanies the gain in cohesiveness.

† Reports, Geological Survey of Kansas, Vol. 5, p. 167.

9. Strength of Plasters. Trade conditions in the plaster industry have not yet reached the point where contracts for plasters are made contingent upon their satisfactorily meeting the requirements imposed by a series of physical and mechanical tests, as is the case in the Portland cement industry. In consequence, scientific investigation of the properties of plasters has been undertaken to a very limited extent only, and the value of the scanty data which bear upon the question, and which are available mainly in the publications of the various State geological surveys, is impaired by the fact that, methods of examination not having been standardized, each investigator has applied whatever tests he may have deemed advisable, though all have followed more or less closely the methods of cement testing, which have been fairly well standardized.

Tensile Strength

The tensile strength of plasters is dependent upon so many considerations incidental to methods and conditions of testing that little data as to tensile strength in general will herein be introduced. Discussion of the subject will largely be devoted to a consideration of the effect of various factors upon tensile strength as shown by comparative tests made in a similar manner under identical exterior conditions.

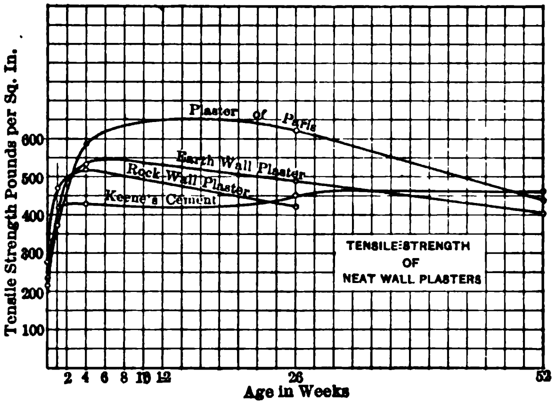

Fig. 3.

Tensile strengths of a number of varieties of plasters are shown by Fig. 3, which is a summary of tests made in the laboratory of Washburn College under the direction of Dr. G. P. Grimsley of the University Geological Survey of Kansas.* Briquettes of the standard form used for cement were molded one at a time from a plaster-water mixture of rather stiff consistency. Storage throughout the period of testing was in the air of the laboratory, and breakage was accomplished in one of the common types of cement briquette-testing machines. The percentage of water used was such a one as was found for each particular

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* Geological Survey of Michigan, Vol. 9, pp. 168–169.

plaster to be sufficient to moisten the plaster so that, when struck with a trowel, a moist surface would appear but no water be caused to stand on the surface. This amount varied for different plasters between the limits of 26.3 and 40.0 per cent. The curves are averages of the results obtained in from 3 to 6 tests of each brand of plaster. One brand of plaster of Paris was tested, two brands of hard wall plaster made from gypsite, three brands of hard wall plaster made from rock gypsum, and one brand of Keene's cement.

The relative strengths of the various plasters shown by the curves should not be accepted as conclusive evidence that plaster of Paris is superior in strength to hard wall plasters, and that plasters made from earthy gypsum excel those made from rock gypsum. Other tests do not always confirm this showing, and the variation on the results of individual tests is too great, and the number of tests too small to make the results of these tests altogether dependable. The curves do illustrate, however, certain characteristics of plasters which have been universally observed, viz.:

> (1) The gain in strength of neat plasters is very rapid for the first few days only;
>
> (2) The maximum tensile strength of neat plasters is attained in a period of from two to four weeks, after which retrogression in strength invariably occurs except in the case of hard-finish plasters.

The actual values of neat tensile strength shown by these plasters (about 400 to 500 pounds per square inch at one week and 400 to 600 pounds per square inch at one month) are probably 50 to 100 per cent higher than the values usually attainable in practice, because of the lower water percentages and the greater degree of compacting utilized by the investigator in comparison with conditions possible in construction work.

The comparative strength of neat hard wall plaster and various sand mortars is shown by the curves of Fig. 4 which constitute a summary of a series of tests made by Professor A. Marston of Iowa State College.* These curves represent the average results obtained in tests of two brands of hard wall plaster, from 3 to 5 separate tests having been made on each brand. It appears from the curves that the tensile strength of a mortar containing 1 part of sand to 1 part of plaster is about 86 per cent of the strength of neat plaster; that mortar containing 2 parts of sand to 1 part of plaster possesses 50 to 60 per cent of the strength of neat plaster; and that mortar containing three parts of sand to 1 part of plaster possesses

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* Iowa Geological Survey, Vol. 12.

about 33 per cent of the strength of neat plaster. The fact must not be overlooked in this connection that the strength of mortar mixtures is largely dependent upon the character of the sand used, the prevailing size, granulometric composition, cleanliness, sharpness, etc.*

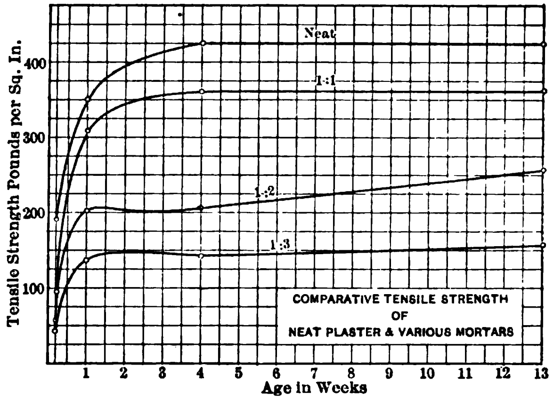

Fig. 4.

One other consideration which considerably affects the sand-carrying capacity of a plaster is the degree of fineness possessed by that plaster. This fact is illustrated by Fig. 5, which affords a comparison of the strength of a 1 : 2 mortar, the plaster being used as marketed, and a similarly proportioned mortar, the plaster used being only that portion of the original sample which has been passed by a sieve of 100 meshes per lineal inch. These curves represent the average of from 3 to 5 tests upon each of two brands of plaster. The curves are based upon data secured by Professor Marston in the series of tests cited in the preceding paragraph. It appears that an advantage in tensile strength in mortar mixtures of about 15 per cent would be secured were all of the plaster fine enough to pass the 100-mesh sieve. The advantage of increased fineness is therefore sufficient to be taken account of, but it is far less marked in plasters than it is in Portland cement, as will be later noted. Indeed, it is not improbable

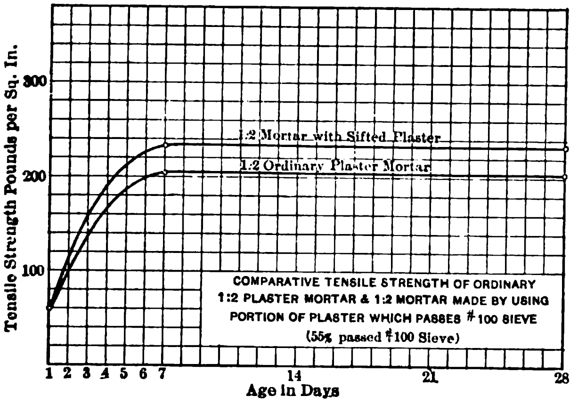

Fig. 5.

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* See discussion of sands for mortars, pages 151 to 154 incl.

that the superiority of the finer particles of plaster over the unsifted article is due simply to the fact that the sifting process has excluded a certain amount of insufficiently calcined material. (It will be recalled that the process of calcination results in the removal of the water by the formation of steam, the expansive force of which is responsible for the fine disintegration of the product. All material which fails to pass the 100-mesh sieve, and a considerable portion of that which does pass this sieve, is probably not a true half-hydrate but contains a certain amount of excess water which impairs its ability to set and harden.)

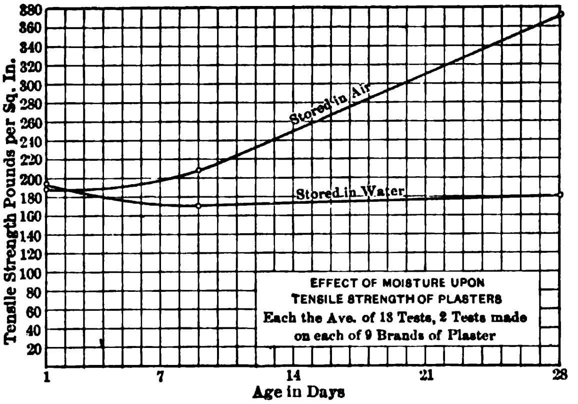

Fig. 6.

The effect of the presence of excess moisture during the period of hardening is shown by the curves of Fig. 6. These curves represent the average results obtained in two tests of each of nine brands of plaster tested by Professor Marston. The fact is strikingly brought out that the average plaster, which after twenty-eight days in air shows a gain in tensile strength of 102 per cent over its one-day strength, absolutely does not gain at all when stored in water twenty-seven days after having hardened in air for twenty-four hours. This fact lends weight to the hypothesis that the retrogression in strength characteristic of all plasters after about one month in air is partially due to the assimilation of excess moisture from the atmosphere. The fact must not be lost sight of, however, that increase in hardness and strength is accompanied by increased stiffness and brittleness. This condition results in increased difficulty in so applying the load in testing as to secure a practically uniform distribution of same on the minimum cross-section of a briquette. With a less stiff and brittle material deformation of the specimen to equalize the stress distribution will have occurred long before rupture, but if such deformation does not occur, or if it is not sufficient to accomplish the end desired, the specimen is subjected to some degree of bending and breaks under an average stress far below the actually existent stress in the extreme fiber on the side where rupture started. It is undoubtedly a fact that the apparent retrogression in tensile strength of practically all cements and plasters, after hardening has progressed beyond a certain point, is in large part due to increased stiffness and brittleness and to the deficiencies of the test above noted.

Compressive Strength

The compressive strength of plasters is dependent upon practically the same factors as the tensile strength, but the experimental determination of compressive strength is fraught with so great difficulties, the results influenced to so large an extent by the personal factor in making and testing specimens, that sources of satisfactory experimental data are almost entirely lacking.

Fig. 7 presents the results of a limited series of compression tests of cement plasters and 1 : 2 mortars made upon prisms 2 by 2 inches in section and 4 inches high, by the Wyoming Geological Survey.* The curves are averages of four tests upon each of two brands of hard wall plaster. A maximum average neat strength of 2565 pounds per square inch and a maximum average mortar strength of 1595 pounds per square inch are shown at the age of one month. Retrogression between the ages of one month and six months, however, is only slight and one of the two brands averaged even showed a considerable gain in strength during this period. The very slight amount of retrogression in compressive strength, as compared with that observed above in the discussion of tensile strength, appears to be in a measure corroborative of the explanation of the causes of retrogression in tensile strength above advanced. There is no reason why the effect of moisture absorbed should not be operative in the case of compressive tests as well as in tensile tests, but increased stiffness and brittleness would not affect compressive strength, because the bearing surfaces of compressive specimens can easily be made to receive a practically uniform load distribution.

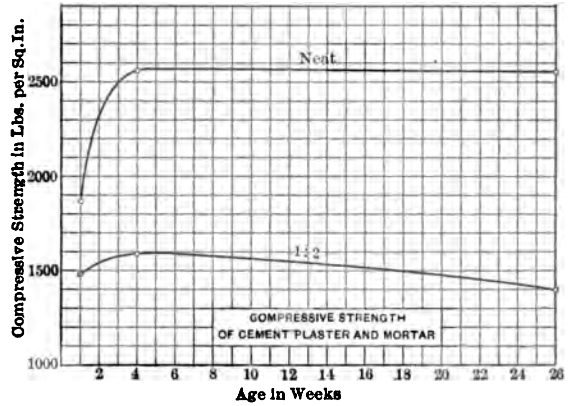

Fig. 7.

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* Geological Survey of Michigan, Vol. 9, p. 176.

The effect of the addition of retarders upon the compressive strength of cement plasters is shown by Fig. 8, which has been plotted from the published tests of Professors Slosson and Moudy of the Wyoming Agricultural and Mechanical College.* The tests were made upon 2-inch cubes, each of the curves of Fig. 8 representing the results obtained upon one brand of plaster.

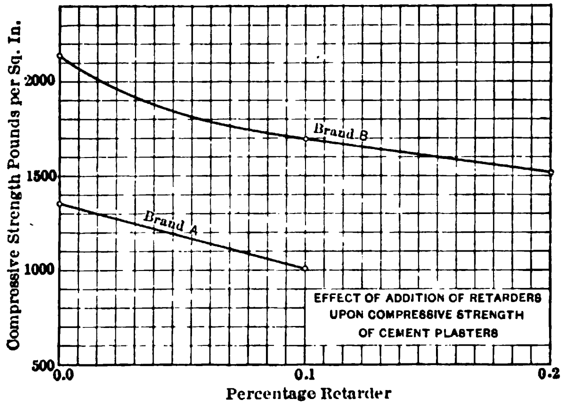

Fig. 8.

No data have been found to establish the facts as to the effect of retarders upon tensile strength. From the analogy to the case of the relative injurious effect of organic matter upon the compressive and the tensile strength of Portland cement, it may be stated, however, that it is improbable that the injurious effect of retarders upon tensile strength of plasters is as marked as it is in the case of compressive strength.

Adhesive Strength

The addition of plaster to various surfaces like that of stone, brick or plaster is a property of this class of building material which should be considered of greatest importance. Very little experimental data bearing upon the subject are available, however.

The results of a limited series of tests made by Dr. Grimsley † are summarized by curves I and II, Fig. 9. In these tests plaster half-briquettes which had been broken at the center and whose fractured surface was fairly smooth were placed in molds and the remaining half filled with new plaster after the surface of the hardened plaster had been thoroughly wetted. The curves average the results from three to nine tests of one brand of cement plaster. It was observed in connection with these tests that, when the surface of the old plaster was not wet, there was scarcely any trace of adhesion.

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* Tenth Annual Report, Wyoming Agricultural and Mechanical College.

† Geological Survey of Michigan, Vol. 9, p. 179.

The result of a similar series of tests made by Professor Marston are summarized by curves III and IV, Fig. 9. The test specimens were made "by taking pieces of No. 2 paving-brick from Des Moines and grinding them on the emery wheel so as to make approximately 1-inch cubes. Each cube had one face carefully trued to give a cross-section exactly 1 inch square. These pieces of paving-brick were placed in the cement briquette molds with this true surface exactly at the middle of the mold. The plaster or stucco was placed to fill the other half of the mold, while the half in which the piece of brick was placed was filled with neat Portland cement mortar." No statement is made as to whether the surface of the paving brick was wet before placing the mortar. The curve III representing the adhesion of plaster of Paris to paving brick is the average of three tests on three different brands, while the curve IV representing the adhesion of cement plaster to paving brick is the average of eight tests on eight different brands. Tests of a similar series of specimens which were stored in water after the first twenty-four hours showed that the excess of water during the period of hardening reduced the adhesive strength about one-third.

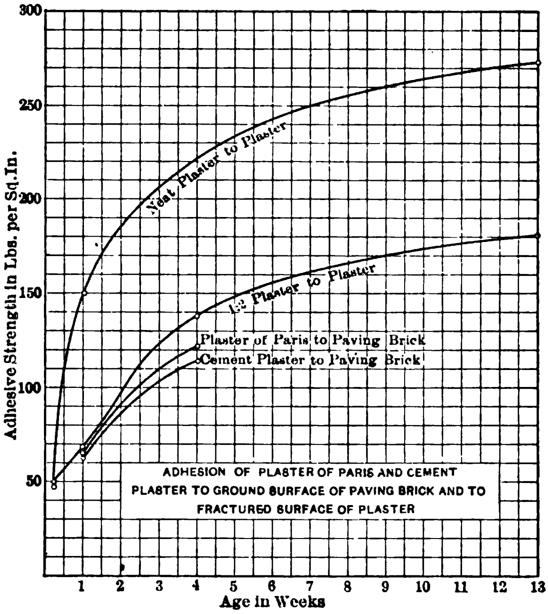

Fig. 9.

10. Relative Applicability of Various Gypsum Plasters to Structural Uses. Plaster of Paris, because of the extremely rapid set which especially fits it for various special uses as a casting plaster, etc., finds very little application as a material of engineering construction. Almost its only structural use is in the form of molded ornaments of "stucco" which serve as architectural adornment of buildings. Stucco is less clear white than pure plaster of Paris, and is less finely divided. Plaster of Paris is not adapted for use as either a wall plaster or a mortar for masonry construction unless additions be made to retard its set and make it more workable. If this is done, however, it is no longer called plaster of Paris, but becomes a cement or hard wall plaster.

Cement or hard wall plasters find their principal applications as wall plasters with which a certain amount of hair, wood fiber, or asbestos fiber, together with hydrated lime or clay, has been mixed at the place of manufacture. Gypsum wall plasters possess a number of advantages over ordinary lime plasters, but also suffer by comparison with lime plasters in certain other respects.

Among the advantages of gypsum plasters, the most important one is the fact that the material comes upon the work ready to be simply mixed with sand and water and immediately applied to the lath, whereas the lime requires careful slaking and should be allowed to season for at least a day, and preferably for a much longer period, before being made up in a mortar and applied to the walls. Secondly, gypsum plasters set more rapidly and dry out in a much shorter time than do lime plasters, thus often avoiding a delay in the completion of the interior finish of buildings.

On the other hand, no gypsum product makes as plastic and smooth working a plaster as does the best lime, provided the latter is properly slaked, seasoned, and mixed. Lime plasters excel in sand-carrying capacity, making it possible to use three or four parts of sand to one of lime for the first or " scratch " coat on walls, and two parts of sand to one of lime for the second or " brown " coat, whereas it is inadvisable with most gypsum plasters to use mortar mixtures leaner than 1 : 2 for either scratch or brown coat on account of their poor spreading qualities. The finish or " skim " coat is a neat or nearly neat paste in either case. This condition tends to make lime plaster cheaper, other things being equal.

It is strongly claimed by those interested in the exploitation of gypsum plasters that this class of wall finish is less injured by moisture; less subject to volumetric change and consequent cracking due to variation in either moisture content or temperature; that it does not affect coloring matter incorporated in the mix as do some limes; that it excels lime plaster as a fire retardant especially when mixed with asbestos fiber; and that it is a superior material from the standpoint of cleanliness and sanitation on account of the smooth polished surface that can be given to it.

All of these latter claims are denied by those interested in the marketing of lime and, in addition, the counter claims are made that gypsum plasters cause wood lath to swell and buckle; that they corrode metal lath; that they are more resonant and less sound-proof; and that they produce an undesirably hard and brittle wall surface.

It will be apparent that these conflicting claims are inspired by the intense trade rivalry that exists between the gypsum interests and the lime interests. For the most part the claims of neither are supported by dependable data, and it is an indubitable fact that wall surfaces may be and often have been built of each material which are entirely satisfactory in every way. The structural qualities of each material are largely dependent upon the way it is used on the work, and the choice of one or the other should depend upon whether the conditions of the work and the experience of the builder are the most favorable to the production of the best results that can be obtained with one material or the other.

Among the applications of hard wall plaster other than as a plaster, the following are worthy of brief notice: Mixed with finely ground cinders and water to form a fluid mix, hard wall plaster is poured in forms for floor panels of fire proof buildings. Mixed with sawdust it is molded into blocks which may be nailed in place as a wall finish, and, without the sawdust it may be molded into solid or hollow building blocks and tiles for the construction of partition walls and floors. A recent special application of cement plaster is in the construction of so-called "plaster-board," wherein the plaster is laminated with thin layers of card-board or wood in sheets which are ready to be nailed to the studding of partition walls. The wall surface thus provided is subsequently plastered, as a rule, but may be finished in panels with no additional plaster by simply covering the joints with wood strips.

Flooring plaster is, as the name implies, intended primarily as a surface finish for floors. It must be protected from moisture while setting, and must dry evenly to avoid the formation of cracks. After standing about twelve hours it is pounded with wooden mallets and smoothed with trowels. Flooring plasters have been used considerably in Germany, but have never been made or used in the United States.

Hard-finish plasters find their principal application as wall plasters and as floor surface, one of the most common applications being as an imitation of tiling or marble for floors and wainscoting in hospitals, lavatories,etc. Keene's cement * is, perhaps, the best known variety of hard-finish plaster. Its set is extremely slow, and it gains in strength very gradually, but ultimately attains a great degree of hardness and a strength exceeding that of any ordinary gypsum plaster. It may be regaged with water after having become partially set, and will then take its set and harden just as satisfactorily, apparently, as if the process of hardening had not been interrupted.

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* The original patent on "Keene's cement" has long since expired and many plasters made both in Europe and in the United States are marketed under this generic name.

11. Production, Value, and Uses of Gypsum Products. Statistics of the gypsum and plaster industry are presented in the table below. These data have been abstracted from the reports of the U. S. Geological Survey, published in the annual volume entitled "Mineral Resources of the United States."

STATISTICS OF THE GYPSUM AND PLASTER INDUSTRY

Year.................. No. of mills reported....	1910 (82)		1911 (78)		1912 (76)		1913 (67)	
	Quantity, Short Tons.	Value per Ton.	Quantity, Short Tons.	Value per Ton.	Quantity, Short Tons.	Value per Ton.	Quantity, Short Tons.	Value per Ton.
Sold without calcining:								
For Portland cement..	334,815	$1.56	327,953	$1.48	382,952	$1.33	408,221	$1.47
As land plaster.......	53,815	2.05	52,880	1.85	53,065	2.02	54,815	1.75
For other purposes....	33,199	1.10	6,647	1.13	5,591	1.26	100	2.00
Total...........	421,829	1.59	387,480	1.52	441,608	1.41	463,136	1.51
Sold calcined:								
For dental plaster.....	115	7.00	413	6.32	3,190	4.88	861	4.84
For plaster of Paris, and wall plaster, including Keene's cement............	1,483,046	3.78	1,523,263	3.73	1,678,417	3.46	1,680,157	3.49
To glass factories.....	15,943	1.83	33,472	2.40	24,159	2.18	10,942	1.99
For Portland cement and other purposes.	84,565	2.65	41,270	2.70	25,908	2.55	81,889	2.36
Total...........	1,583,669	3.70	1,598,418	3.67	1,731,674	3.43	1,773,849	3.43
Grand total......	2,005,498	3.25	1,985,898	3.25	2,173,282	3.02	2,236,985	3.03

CHAPTER II

QUICKLIME

GENERAL

12. Definition and Classification.* Quicklime is the name applied to the common or commercial form of calcium oxide (CaO), obtained by the calcination below the sintering point of a stone in which the predominating constituent is calcium carbonate ($CaCO_3$), often replaced, however, to a greater or less degree by magnesium carbonate ($MgCO_3$), this product being one which will slake on the addition of water.

Hydrated lime is absolutely the same material as quicklime except that it does not possess the power of slaking, since it has been chemically satisfied with water during manufacture.

Quicklime is divided into two general grades:

(*a*) *Selected.* A well-burned lime, picked free from ashes, core, clinker, or other foreign material, containing not less than 90 per cent of calcium and magnesium oxides and not more than 3 per cent of carbon dioxide.

(*b*) *Run-of-kiln.* A well-burned lime without selection, containing not less than 85 per cent of calcium and magnesium oxides and not more than 5 per cent of carbon dioxide.

According to the physical form of the material, quicklime is marketed as:

(*a*) *Lump Lime.* The size in which it comes from the kiln.

(*b*) *Pulverized Lime.* Lump lime materially reduced in size by mechanical means.

According to relative content of calcium oxide and magnesium oxide, quicklimes are divided into four types:

(*a*) *High-calcium.* Quicklime containing 90 per cent or over of calcium oxide. (Sometimes termed " rich," " fat," or " caustic " lime.)

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* The classification is that proposed June, 1914, by Committee C–7 of the Am. Soc. Test. Materials.

(*b*) *Calcium.* Quicklime containing not less than 85 per cent and not more than 90 per cent of calcium oxide.

(*c*) *Magnesian.* Quicklime containing between 10 and 25 per cent of magnesium oxide.

(*d*) *Dolomitic.* Quicklime containing over 25 per cent of magnesium oxide.

All of the above limes are sometimes classed as "white limes" in contradistinction to the "gray limes": hydraulic lime, derived from limestones containing from 5 to 20 per cent of clayey and sandy material (silica and alumina), and natural cements, made from limestones containing from 15 to 35 per cent of clayey and sandy material.

13. The Place of Lime* Among Cementing Materials. Cementing materials used structurally may be divided into two general classes, as *non-hydraulic* and *hydraulic.* Lime is the most common non-hydraulic cementing material, and the only one of any commercial importance except the gypsum plasters discussed in Chapter I. The hydraulic cements include hydraulic limes, grappier cements, natural cements, Portland cement, and puzzolanas. Each of the hydraulic cements will be treated in the chapters which follow.

14. Application in the Arts and Industries. Although the applications of lime in the various arts and industries are innumerable, the most important ones are briefly mentioned in the following list:

Natural cement manufacture, added prior to final grinding in hydrated form, beneficial to strength and smooth working qualities. High-calcium lime is necessary.

Sand-lime brick manufacture, mixed in hydrated form with sand, and subsequently molded into bricks which are hardened by high pressure steam. High calcium lime is necessary.

Gypsum plaster manufacture, added subsequent to calcination in hydrated form, beneficial from the standpoint of working qualities. Either high calcium lime or magnesian lime satisfactory.

Slag cement and puzzolan cement, mixed in hydrated form with granulated blast-furnace slag or puzzolan and subsequently ground to form an inferior grade of hydraulic cement. High calcium lime necessary.

Iron and steel manufacture, used as raw limestone or lump lime as a flux in blast furnaces and steel furnaces to render fusible the mechanical impurities and furnish a liquid slag to carry off both mechanical and chemical impurities. Either high-calcium or magnesian limestone satisfactory.

Glass manufacture, used in the form of ground quicklime in combination with sand and sodium carbonate as the base of all glass mixtures. Magnesian lime usually preferred.

Paper manufacture, in soda process quicklime is used to recover caustic soda from liquor in which wood has been cooked to make pulp; in sulphite process either raw

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* The term "lime" when used herein is intended to include both quicklime and hydrated lime.

limestone or slaked lime in form of milk of lime is used with sulphur dioxide to form bisulphites which are held in solution by excess SO_2 thus constituting a liquor in which wood is cooked to make pulp. Magnesian limes preferable.

Sugar manufacture, used in the form of the purest calcium oxide obtainable to remove impurities in juice of beet or cane, the lime being subsequently liberated from sugar by introduction of CO_2. High calcium limestone is burned by sugar manufacturer who uses both CaO and CO_2.

Soda ash manufacture, used as ground lime to recover ammonia used in the process. High calcium lime preferred.

Bleaching powder manufacture, used as ground lime as absorbent for chlorine gas. Purest high calcium lime required.

Illuminating gas manufacture, gas distilled from coal is freed from CO_2, H_2SO_4, etc., by passing through moist slaked lime. Ammonia is also freed from by-products by action of lime which takes up acids, heavy oils, etc. High calcium lime required.

Wood-alcohol, acetic acid, and acetone derivation, the pyroligneous acid first derived by distillation of wood is redistilled in excess of lime, producing "gray acetate of lime" and freeing the wood alcohol. The latter is purified by redistillation with lime. Acetone is obtained from the acetate by dry distillation, and acetic acid by distillation after treating with sulphuric acid. High calcium lime desirable.

Calcium carbide manufacture, a mixture of lime and coke is heated to an extreme degree in the electric furnace. The product is the source of acetylene. Purest high calcium lime required.

Glycerine derivation, the treatment of fats with quicklime results in the liberation of glycerine and the formation of lime-soaps by combination of the lime with the organic acids. Either high calcium or magnesian lime satisfactory.

Heavy lubricants, lime-soaps derived as above noted, mixed with mineral oils, form lubricants satisfactory for use with heavy machinery or at high temperature.

Waterproofing compounds, lime-soaps derived as above noted, or as a by-product of soap manufacture, form the base of most so-called active waterproofing compounds, used especially in cement mortars and concretes to reduce permeability.

Cold-water paints, mixtures of hydrated lime, lime carbonate, or air-slaked lime with pigments and casein form the bulk of that class of paints which are not prepared for use by mixing with oils. Magnesian limes preferred.

Tanning industries, soaking of hides in a lime-water bath loosens the hair so that it can be scraped off. High calcium limes preferred.

Water purification, "temporary hardness" of water, caused by presence of $CaCO_3$ held in solution by excess CO_2, is removed by treatment with hydrated lime, which takes up CO_2, forming additional $CaCO_3$ which, together with that originally present, precipitates out. High calcium lime preferred.

Agricultural uses, used in connection with some organic fertilizer as a soil amendment to convert nitrogen of the air into nitrates available as plant food. A definite ratio of magnesium oxide to calcium oxide is desirable for a given soil.

A lime-water is also used for spraying purposes as an insecticide.

15. Structural Uses. The applications of lime as a structural material are very few in number compared to its applications in various manufacturing and chemical processes. The total amount used structurally, however, far exceeds the amount used for any single industrial purpose and, indeed, amounts to two-fifths of the total amount of lime marketed for all purposes.

By far the largest portion of the lime used as a building material is used in combination with sand as a mortar for use in laying brick and stone masonry. Another large portion is used as a wall plaster, and the greater part of the balance is used in gaging cement mortars either for the purpose of increasing their plasticity, thus making them easier to work, or to reduce their permeability. A small amount of lime is used structurally as a whitewash.

In the present chapter the use of lime in mortars and plasters will be alone considered. Its use in connection with cements will be discussed in the chapters devoted to the properties and uses of natural and Portland cement.

MANUFACTURE OF LIME

16. Limestone Rocks. An ideal, pure limestone consists entirely of calcium carbonate ($CaCO_3$) which, at a temperature of 898° C. or over, becomes dissociated, the carbon dioxide (CO_2) being driven off as a gas, leaving behind a white solid, calcium oxide or quicklime (CaO).

As the original calcium carbonate consisted of 56.1 parts by weight of CaO to 44.0 parts of CO_2, the theoretical proportion of quicklime obtainable by the calcination of limestone will be 56.0 per cent by weight. In practice, the proportion of quicklime obtainable will always fall below this theoretical limit on account of the inevitable presence of impurities in the limestone and the imperfections of the process of calcination.

Limestones encountered in practice depart more or less from this theoretical composition. A part of the lime is almost invariably replaced by a certain percentage of magnesia (MgO), making the stone to a greater or less extent a magnesian limestone. In addition to magnesia, silica, iron oxide, and alumina are usually present to an appreciable extent, and, to a slight extent, sulphur and alkalies.

17. Theory of Calcination. The burning or calcination of lime is a very simple chemical process known, in its essentials at least, since very ancient times. Three objects are accomplished by burning the limestone:

(1) The water in the stone is evaporated.

(2) The limestone is heated to the requisite temperature for chemical dissociation.

(3) The carbon dioxide is driven off as a gas, leaving the oxides of calcium and magnesium.

The evaporation of any water present in the stone means that a certain portion of the heat supplied during calcination does not directly assist in the dissociation of the carbonates. This heat does not mean a thermal loss, however, because the presence of the water, and the steam generated from it, facilitates the dissociation process, as will be hereinafter shown.

The temperature of dissociation of pure calcium carbonate at a pressure of one atmosphere has been determined by Johnson * to be 898° C., and the corresponding temperature for magnesium carbonate is generally stated to be between 550° and 750° C. If the magnesium occurs in the stone not as a simple carbonate, $MgCO_3$, but in combination with the calcium carbonate as dolomite, $CaCO_3$, $MgCO_3$ (as may possibly be the case), the temperature of dissociation cannot be stated precisely. The studies of Professor Bleininger and Mr. Emley † tend to show that the maximum calcination temperature for high-calcium lime low in impurities is not below 1300° C.; that for high-calcium lime high in impurities the maximum temperature is from 1050° to 1200° C., and that for magnesian lime low in impurities the maximum temperature is 900° to 1050° C. The minimum dissociation temperature of calcium carbonate was found to be remarkably constant for most stones in the neighborhood of 880° C., and the corresponding minimum dissociation temperature for magnesium carbonate was found to be about 750° C., although this point was found to be more variable than that for the calcium carbonate.

Theoretically, all limestones could be properly burned at a temperature of about 880° C., provided sufficient time be allowed. In practice, however, the maximum kiln output is always striven for, and, since the rate of heating is directly proportional to the temperature of the kiln, the maximum kiln output is obtained by burning at the highest temperature practicable. The highest temperature practicable is not the highest temperature attainable, however, because the increased activity of the impurities with rising temperature set a very definite maximum limit, the exceeding of which means serious injury to the quality of the lime produced.

The impurities in limestones are all essentially acids which readily combine with the basic lime and magnesia. The silica forms silicates of lime and magnesia, the alumina forms aluminates, and the iron oxide forms ferrites. These silicates, aluminates, and ferrites are all readily fusible compared with pure lime or magnesia, and the result of their formation with increasing temperature is a softening of the portion of the stone thus rendered fusible at the practical dissociation temperature, and its softening closes up the pores and envelopes the particles of lime

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* Journal Amer. Chem. Soc., 1910, p. 938.

† The Burning Temperature of Limestone, Trans. Nat. Lime Manf's Assoc., Feb., 1911, pp. 68–78.

with a slag-like coating which causes the quicklime to slake with difficulty, and which therefore greatly injures the commercial value of the kiln product. The softening of the mass also results in compacting the material, thereby further injuring its qualities by mechanically rendering it less porous.

This behavior on the part of the impurities explains the existence of maximum practical temperature limits in burning impure limestones, exceeding which causes marked loss of power of the quicklime to combine with water in slaking, whereas it is practically impossible to overburn pure limestone.

The physical character of the limestone has an important bearing upon the burning temperature, quite aside from the question of chemical composition. A naturally coarse, porous stone is much more rapidly acted upon by heat than a dense, finely crystalline stone, and in consequence may be burned more rapidly and at a lower temperature. Small pieces of stone may also theoretically be burned more readily than large stones. In practice, however, large sizes seem to be preferred by the practical lime manufacturer, the common practice being to use what are called "one-man-stone," measuring about 8 to 10 inches in diameter.

One other consideration affecting calcination temperatures which cannot be overlooked is the fact that the temperature required to effect calcination at atmospheric pressure need not be attained under actual working conditions, for the simple reason that provision is made for sufficient draft in the kiln to prevent the internal gas pressure ever becoming so much as one atmosphere.

The necessity for provision for carrying off the carbon-dioxide gas evolved during calcination has just been indicated. The necessary calcination temperature being directly dependent upon the pressure, it would be very uneconomical of fuel to allow the gas to accumulate. It is possible, in fact, when the pressure is allowed to increase without a proportional increase in temperature, to actually reverse the process of dissociation and cause the carbon-dioxide to recombine with lime and magnesia and reform their carbonate. This phenomenon is known technically as "recarbonating." (Recarbonating is especially apt to occur in mixed-feed kilns and also in separate-feed kilns if fuel is allowed to fall over the bridge wall into the cooler.) Various expedients are adopted in practice to maintain the gas pressure at as low a point as possible, the most common one being the introduction of jets of steam or water into the hottest portion of the kiln. Upon contact with the glowing carbon of the fuel, the water is robbed of its oxygen, a certain amount of heat being required to effect the chemical decomposition. The hydrogen travels toward the stack end of the kiln until it encounters a temperature at which recombination with oxygen is possible. The reformation of water vapor is attended by the evolution of the same amount of heat as was utilized in effecting dissociation of the original water vapor, resulting in increasing the draught and decreasing the gas pressure. This practice is attended by another thermal advantage in that it tends to equalize the heat distribution throughout the material in the kiln. Heat is taken from the overheated portion of the kiln and restored where most needed. Increased kiln efficiency is therefore attained.

18. Practice of Calcination. The types of kilns employed in lime burning may be briefly described as follows:

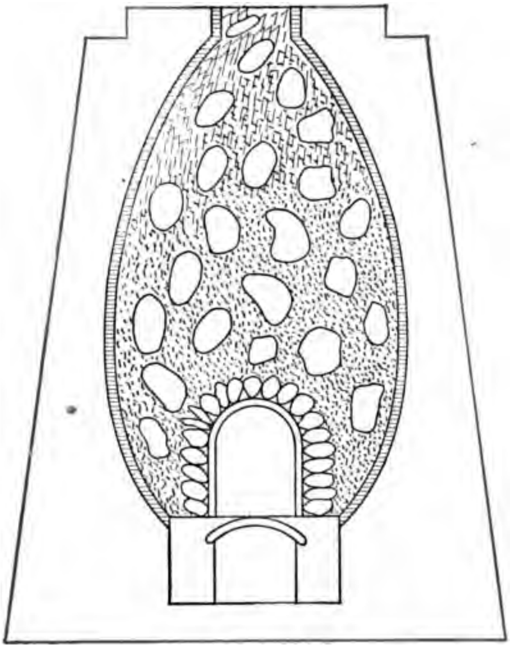

FIG. 10.—Pot Kiln for Lime Burning.

Intermittent Kilns. An early form of intermittent kiln consisted simply of a dome-like structure crudely constructed by using the larger blocks of the stone to be burned. The balance of the limestone was piled on top and a wood fire started underneath. A bright red heat having been obtained throughout the mass of stone, this temperature was maintained for a period of three or four days, when, the mass having become soft, the fire was allowed to go out and, after cooling, the lime was removed, the structure being demolished in so doing.

Permanent intermittent kilns, often called "pot kilns" (Fig. 10), built of stone with a firebrick lining and provided with a grate upon which the fuel is placed, gradually replaced the original type. These kilns are provided with an arched opening at the bottom through which fuel is introduced and the burnt lime removed. The fuel consumption of even this type of intermittent kiln is very excessive, due to the necessity of heating the entire mass of masonry, as well as the contents, to the required temperature of calcination each time the kiln is charged. In addition, the product is never uniformly burned.

Continuous Kilns. (*a*) *The Vertical Kiln with Mixed Feed.* In this kiln (Fig. 11), the fuel (bituminous coal) and the limestone are charged in alternate layers, the lime being removed at the bottom while fresh fuel and limestone are charged in at the top. The fuel consumption usually amounts to from 15 to 25 per cent of the weight of lime produced. Few mixed-feed kilns are now employed in the American lime industry.

(*b*) *The Vertical Kiln with Separate Feed.* The kilns of this type (Fig. 12) are so designed that the fuel and limestone do not come in contact, the fuel being burned in separate fireplaces either set in the wall of the kiln or outside the kiln shell. The limestone therefore comes in contact only with the hot gaseous products of combustion.

The relative advantages of types (*a*) and (*b*), which are almost exclusively used in the United States, may be summarized as follows: The mixed-feed kilns are cheaper to construct, somewhat more economical of fuel, and somewhat more rapid in operation. On the other hand, the separate-feed kilns yield a lime somewhat less discolored by contact with the fuel, the lime is free from the fuel ash, which is not easily separated out, and the danger of some part of the lime being imperfectly calcined, owing to a coating of fuel clinker on the lumps, is obviated. From 75 to 80 per cent of the output of the mixed-feed kiln is marketable as well-burned, clean, white lime as compared with 90 per cent obtainable from separate-feed kilns.

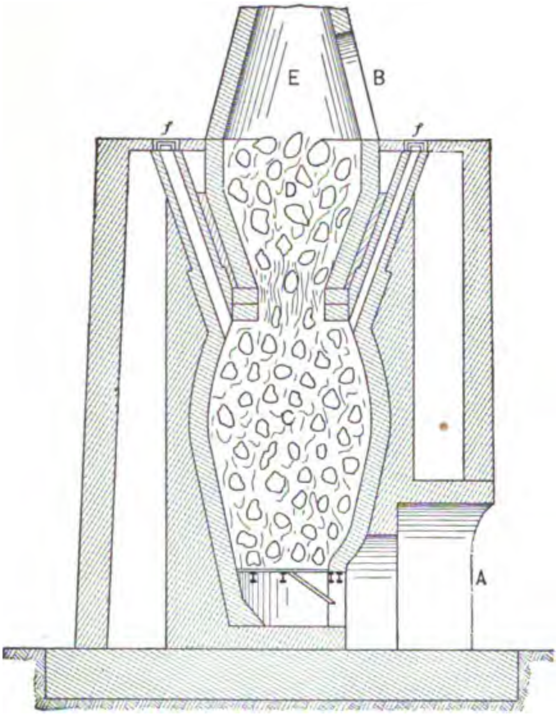

FIG. 11.—Aalborg Kiln for Lime Burning.

The present tendency among American lime manufacturers seems to be in the direction of building large separate-feed kilns having a capacity of 50 to 60 tons per day of twenty-four hours, instead of the usual type of kiln with a capacity of 8 or 10 or possibly 15 tons per day.

(*c*) *Ring or Chamber Kilns.* The ring kiln has been used quite extensively in Germany and other parts of Europe, but has never come into favor in the United States. The commonest type of ring kiln, the Hoffman kiln (Fig. 13), consists of a series of chambers arranged around a central stack. Each chamber is connected by flues with the stack and with each of the two adjoining chambers, and each flue is provided with a damper by means of which the passage may be closed. The chambers may be charged with limestone and fuel in the shape of fine coal, and one chamber is fired. The dampers are now so set that the hot gases of the burning chamber must traverse all the other chambers before passing to the stack, so utilizing the heat of the gases in preheating the contents of the chambers not yet fired. When the calcination of the limestone in the first chamber is complete, the second chamber is fired and the first chamber is temporarily cut out of the circuit until it has been discharged and recharged, when it becomes the last chamber in the circuit. The operation is continued in this manner indefinitely.

The Hoffman kiln is an improvement both in economy and in quality of product upon the mixed-feed vertical kiln, but its superiority over the most modern American separate-feed kiln is doubtful. In common German practice the fuel consumption amounts to from 20 to 22 per cent of the lime produced, while with careful management the percentage may be kept still lower.

(*d*) *Rotary Kilns.* Rotary kilns, resembling in construction the rotary cement kilns described in the chapter on Portland cement (page 123), have been applied to the calcination of lime to a limited extent. They are subject to the disadvantage of requiring that the stone be finely crushed prior to the calcination, and the product is consequently so finely divided that it is not marketable as lump lime, but can be sold only after grinding or hydrating, as either ground or hydrated lime.

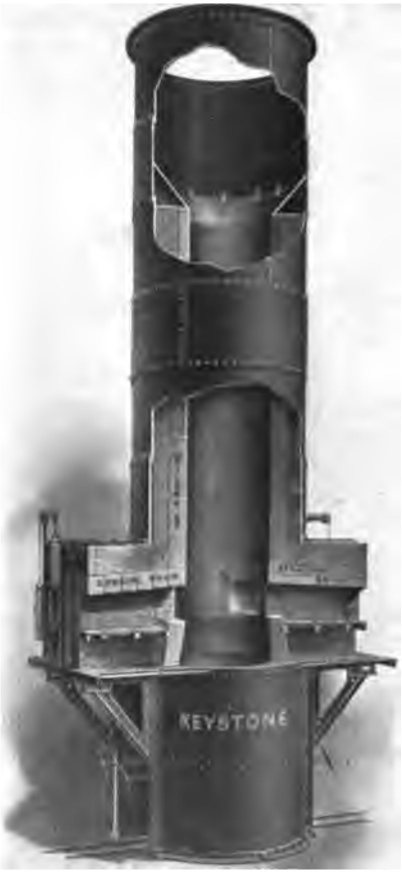

Fig. 12.—Keystone Separate-feed Lime Kiln.

The fuels used in lime burning are wood, bituminous coal, and producer gas. Wood fuel possesses a distinct advantage over coal because of its greater moisture content, which results in longer flames and consequent better heat distribution throughout the mass of stone. Coal would never be used as a kiln fuel were it not for the impossibility of procuring wood fuel in many districts. The short-flaming hot coal fire results in overheating of the portion of the kiln near the firebox, while the material shortly above the fire zone receives far too little heat. The use of producer gas as a fuel for lime burning is a late development both in Europe and the United States, its installation having thus far been largely confined to the larger and more modern plants. The necessary installation consists simply in the replacement of the firebox of the separate-feed kiln by gas producers and burners. The gas and air ports are so placed in the walls of the kiln that the combustion takes place within the kiln chamber itself. The relative advantages of producer gas and coal and wood as a fuel are not yet perfectly established. It is to be expected, however, that while the fuel economy may be slight, there should be some increase in capacity and a decrease in labor costs.

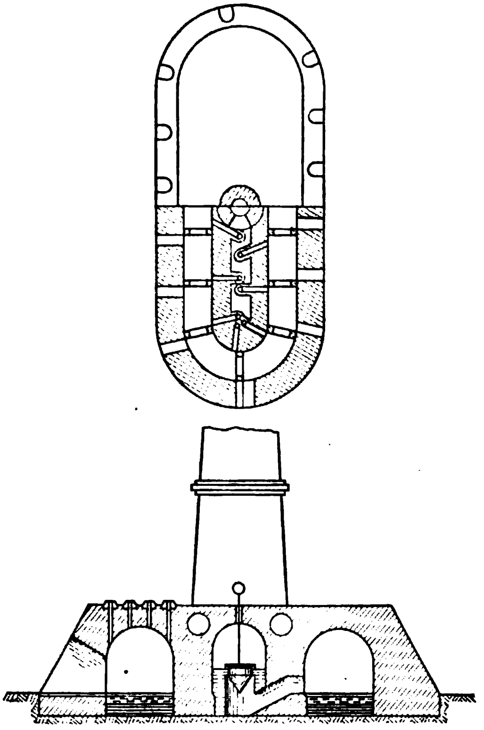

FIG. 13.—Hoffmann Ring Kiln.

The defects of coal as a kiln fuel may be in a measure overcome by the adoption of some expedient which makes possible longer flames or better heat distribution. A forced draught may be obtained by blowing steam in through the grates. The moisture thus introduced is beneficial in that it cools the overheated portion of the charge, mechanically transfers heat to the kiln, and, for other reasons indicated above, lowers the calcination temperature and equalizes the distribution of heat. The action of the kiln and its thermal efficiency are further improved, if an exhaust fan is also provided to draw off the burned gases and prevent the possibility of recarbonation. A practical difficulty which attends the use of steam in lime burning, and which has limited the extent of its application, is the fact that the amount of moisture used must be carefully regulated, a thing not easy to accomplish.

Another method of combining induced and forced draught is that known as the " Eldred process," which consists essentially in exhausting the kiln by a fan and forcing a portion of the burned gases thus derived back under the firebox grates, together with a supply of fresh air. The fire is cooled by dilution of the air with carbon dioxide. In addition, carbon dioxide transfers heat to the stock in the kiln mechanically, and probably also does so chemically, in a measure, a part of the dioxide being reduced in the firebox to the monoxide, which latter gas burns to the dioxide again in the kiln, thus transferring heat in a manner similar in some respects to the action of steam. Carbon dioxide does not lower the calcination temperature as does steam, however, and the merits of the Eldred process in general still constitute a much-debated question among lime manufacturers.

A lime kiln in operation always contains three classes of material: (*a*) Stone undergoing preliminary heating through the agency of the escaping hot products of combustion: (*b*) Stone undergoing dissociation through the agency of the direct heat of the fuel: (*c*) Calcined lime which accumulates in the lower portion of the kiln and is withdrawn in part from time to time. The total amount of lime present in the kiln cannot be drawn at one time, because, aside from the desirability of letting it cool in the kiln itself, enough must remain at all times to fill the "cooler" (that portion of the kiln below the level of the fuel grate), thus preventing unburned stone from sinking below the level of the zone in which it is subjected to the action of the flames of the fires.

The operation of drawing consists simply in opening a draw-door provided in the lower part of the cooler, poking the lime loose with a bar, and allowing it to fall into a barrow or car placed underneath. This operation is repeated at intervals of from one to eight hours (usually from four to six hours).

19. Treatment Subsequent to Calcination. Lime drawn cold from the kiln is immediately ready to be marketed as lump lime. When the kiln is not provided with a cooler, however, or when drawn from the cooler while still very hot, it is necessary to spread it out on a cooling floor or leave it standing in fireproof containers for a few hours before taking it to storage, packing house, or cars. Underburned and overburned material is easily recognized by its appearance, and is sorted out by hand while drawing it into the barrows, or while it lies on the cooling floor. Many consumers of lump lime formerly required that it be screened to remove the fine material, their belief being that the fineness of the lime indicated that it had become air-slaked. This practice was wholly unjustifiable, and based upon a fallacy now commonly recognized as such.

An increasing proportion of the lime intended for use in the building trades, especially as hydrated lime, as well as for agricultural purposes and many applications in the arts and industries, is now ground before being marketed. Ground lime is prepared by running the cooled lime through a crusher and then a pulverizing mill, which reduces it to a size sufficient to pass a sieve of 80 meshes per lineal inch. The product is then barreled or sent to the hydrator. Ground lime used structurally as quicklime is seldom crushed to a size less than about ½ inch.

" Hydrated lime " has come to be regarded as a special product, and its preparation will be separately discussed in the following chapter.

PROPERTIES AND USES OF QUICKLIMES

20. Classification of Limes by Uses. Required Qualifications of Each Class.* Limes may be conveniently classified according to the purposes for which they are used, as (1) agricultural limes, (2) chemical limes, (3) building limes, and (4) finishing limes.

For agricultural limes only the chemical composition is of importance; for limes used in the chemical industries the chemical composition and the rate of hydration are important; building limes must be satisfactory as regards sand-carrying capacity, yield of lime-paste per unit weight of lime, crushing strength, and tensile strength; and finishing limes must be satisfactory with respect to rate of hydration, plasticity, sand-carrying capacity, color, yield, waste (i.e., that percentage of a lime made up into a putty which cannot be washed through a 20-mesh sieve by a stream of water having a moderate pressure), hardness, time of setting, and shrinkage.

21. Chemical Composition. The approximate chemical composition of limes of various classes has been indicated in Art. 12 above, wherein limes were classified and graded according to their content of calcium oxide, magnesium oxide, and carbon dioxide. The following table, which has been abstracted from one published by Mr. Emley of the U. S. Bureau of Standards,† illustrates the range of composition found for limes of various classes upon analysis of thirty-seven samples of quicklimes and hydrates coming from thirty-two different States in the United States:

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* This classification is that proposed by W. E. Emley of the Pittsburgh Branch of the U.S. Bureau of Standards. See Trans. Nat. Lime Manfr's. Assoc., Jan., 1913, pp. 77–100.

† Trans. Nat. Lime Manfr's. Assoc., Jan., 1913, pp. 77–100.

ANALYSIS OF THIRTY-SEVEN QUICKLIMES AND HYDRATES

SUMMARY

Class of Lime.	High Calcium Quicklimes.			Calcium and Magnesian Quicklimes.			Dolomitic Quicklimes.		
Component.	Min. %	Max. %	Ave. of (10) %	Min. %	Max. %	Ave. of (6) %	Min. %	Max. %	Ave. of (2) %
SiO_2....	0.33	2.20	0.81	0.66	9.00[1]	3.12	0.14	1.59	0.87
Fe_2O_3...	0.08	0.43	0.23	0.17	0.59	0.41	0.19	0.39	0.29
Al_2O_3...	0.02	0.42	0.22	0.18	2.57[1]	0.93	0.14	0.49	0.32
CaO....	91.37	98.08	94.98	78.59	84.81	81.42	55.80	64.45	60.13
MgO....	0.17	4.55	1.39	1.03	16.83	9.26	31.61	40.62	36.12
H_2O....	0.36	3.45	1.66	0.63	12.42[2]	4.18	0.55	1.56	1.06
CO_2.....	0.20	1.84	0.83	0.24	1.94	0.18	0.35	3.01	1.68

Class of Lime.	High Calcium Hydrates.			Dolomitic Hydrates.		
Component.	Min. %	Max. %	Ave. of (11) %	Min. %	Max. %	Ave. of (8) %
SiO_2....	0.42	5.03[1]	1.60	0.20	3.78[1]	1.82
Fe_2O_3...	0.10	1.01	0.33	0.15	0.81	0.35
Al_2O_3...	0.23	1.05	0.55	0.20	3.50[1]	1.26
CaO....	66.71	73.45	70.90	40.06	53.20	47.06
MgO....	0.28	4.11	1.68	23.10	34.02	29.92
H_2O....	18.94	24.98	22.45	14.24	21.37	16.77
CO_2.....	0.57	6.25[3]	2.52	0.79	9.81[3]	2.49

[1] Excessively high in acid impurities.

[2] Incipient air-slaking shows.

[3] Excessively carbonated.

22. Hydration or Slaking. Rate of Hydration. Quicklime intended for use in mortars for masonry construction or as a wall plaster must first be prepared for mixing with water to form a lime paste by being slaked. The hydration or slaking of quicklime consists simply in the addition of sufficient water for the formation of calcium hydroxide, the operation being represented by the formula:

$$CaO + H_2O = Ca(OH)_2,$$

$$75.7 + 24.3 = \quad 100 \quad \text{(parts by weight).}$$

If the quicklime were absolutely free from impurities the amount of water required for complete slaking would equal 32.1 per cent by weight of the quicklime, but the fact that the quicklime is always impure to a greater or lesser degree makes the amount of water actually required less than the above percentage. The formation of lime hydrate is attended by the evolution of considerable heat and an expansion to about $2\frac{1}{2}$ or 3 times its former volume. Magnesian quicklimes, and particularly dolomitic quicklimes, slake more slowly than high calcium limes, and the slaking is attended with the evolution of much less heat and far less expansion. The common practice in slaking quicklime for building mortars is to add much more water than is actually required, a practice which with even ordinary care should insure thorough slaking; though it may possibly be at the expense of some loss in mortar strength. The fact that quicklime used in the building trades is so commonly slaked carelessly by unskilled labor is largely responsible for the demand of late years for gypsum plasters and ready slaked lime or " hydrated lime."

Lime intended for use in a mortar is usually slaked in a mortar mixing box, the mixture being stirred as water is added until a thin paste or " putty " has been formed. The putty is thereupon covered with sand to protect it from the action of the air, and is kept so covered until all has been gradually used by mixing with sand to make mortar.

Lime paste or putty designed for use as a plaster was once commonly placed in barrels, covered with an excess of water, and allowed to season for several weeks or even months before being used. The present practice is to greatly shorten the period of seasoning, though the quality of the plaster from the standpoint of workability is greatly injured by the common practice of seasoning overnight or for a few hours only.

The reaction involved in the hydration of quicklime may result in the production of either crystalline calcium hydroxide or colloidal * calcium hydroxide, the relative quantity of one or the other being dependent upon the time afforded for the reaction. Crystals of calcium hydroxide form and grow slowly, whereas the colloidal hydroxide forms with great rapidity. Consequently, the more rapid the reaction is made to be, the greater the proportion of colloidal hydroxide. The reaction may be most readily hastened by using warm water in slaking. A preponderance of colloidal hydroxide is eminently desirable from the standpoint of the mason who judges a mortar by its plasticity or spreading qualities, its yield, and its sand-carrying capacity.

The hydration of high-calcium quicklimes is attended by great danger of " burning," due to too great a rise in temperature. The exact nature of this chemical phenomenon is not understood but the product " burned lime," appears to be chemically inert and is useless in a mortar or plaster. Burning may best be avoided by securing an intimate contact between

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* A colloid is a non-crystalline hydrate which possesses the physical characteristics of a gelatine, and which upon desiccation, may acquire a strong binding power like glue.

every particle of lime and the water. Great watchfulness and continuous stirring of the mixture is therefore necessary.

No danger of burning attends the slaking of most magnesian and all dolomitic quicklimes. On the contrary, the danger in this case is that the quicklime may never be properly slaked before being used. All magnesian quicklimes slake very slowly and, if the temperature of calcination has been very high, hydration may scarcely be possible at all. Dr. Campbell * concluded, as the outcome of a study of this question, that magnesium oxide will combine with water with reasonable rapidity only when it has been burned at a temperature below 1100° C.

The phenomenon known as " air slaking" of quicklime is deserving of mention in this connection, although as will be shown directly, " air-slaked " lime is a very different thing from the ordinary slaked lime. Quicklime exposed to the air absorbs moisture and becomes slaked lime, the expansion accompanying hydration causing the lumps to fall into a more or less fine powder. Immediately, the slaked lime is attacked by the carbon dioxide of the air, the water is replaced by CO_2, and the resulting product is simply powdered calcium carbonate, $CaCO_3$. The term " air-slaked " will be seen to be a very misleading one, for the quicklime has not simply been slaked by the moisture in the air, but has been ruined completely as a cementing material by the taking up carbon dioxide while in a loose powdered state. The fact that quicklime does " air slake " when exposed to the air is not an unmitigated evil, however, because it renders possible the storage and even the shipment of ground lime without its being contained in tight bags or barrels. The quicklime at the surface becomes " air-slaked," but by so doing it immediately forms a film which protects the bulk of the material to which moisture and CO_2 cannot gain access.

The experimental determination of the rate of hydration of quicklimes is accomplished by observation of the increase in temperature accompanying hydration. The method employed by Mr. Emley consisted in observing the temperature increase of water in a special bomb calorimeter during the period of hydration of a sample of quicklime enclosed within the bomb with a measured quantity of water. The rate of hydration is really the slope of the time-temperature curve, but is most conveniently expressed by the time required to attain maximum temperature.

The rates of hydration of various quicklimes were found by Mr. Emley to be dependent, first, upon the physical character of the material, finely divided or porous quicklimes being more quickly hydrating because of their greater accessibility to water; second, upon the chemical composition of the quicklimes, high-calcium quicklimes being more quickly

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* Journal Ind. and Eng. Chemistry, Vol. 1, p. 665.

hydrating than magnesian or dolomitic quicklimes, and pure limes of either class more quickly hydrating than impure ones, because the rate of hydration is largely dependent upon the proportion of calcium oxide —the active constituent—present; third, upon the temperature of burning of the quicklime, any underburned quicklime having little ability to hydrate, and overburned limes behaving similarly owing to the influence of impurities.

The relative rapidity with which pure and impure high-calcium and dolomitic quicklimes hydrate is forcibly illustrated by the curves of Fig. 14. The slopes of the curves indicate the relative rates of hydration, the maximum ordinates indicate the relative amounts of heat generated in hydrating, and the corresponding abscissæ indicate the time required for complete hydration. It will be noted that the rate of hydrations of the high-calcium quicklime is about twice that of the impure high-calcium quicklime, more than twice that of the pure dolomitic quicklime, and fully three times that of the impure dolomitic quicklime. It is also apparent that the heat generated during hydration is much greater for the high-calcium and the pure quicklimes, that the dolomitic quicklime requires twice as long to become completely hydrated as does the high-calcium, and lastly, impure quicklimes require several times as long to hydrate as do the corresponding pure quicklimes.

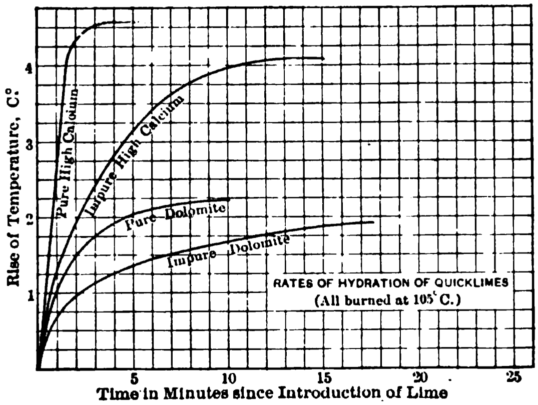

FIG. 14.

All of the quicklimes of Fig. 14 were burned at the same temperature, 1050° C. That the temperature of burning is a factor even more influential than the composition is shown by the curves of Fig. 15, which illustrate the relationship between burning temperature and the ability of quicklimes to hydrate. It is noticeable that the lack of ability to hydrate through underburning is common to all limes, since more or less carbon dioxide still remains in combination with the lime, but that the loss of ability to hydrate, due to overburning, is noticeable at lower temperatures, and is much more marked at higher temperatures, if the quicklime is impure than if the quicklime is pure. This is due to the fact that the impurities may at high temperatures combine with lime to form compounds which will not hydrate, and also because the compounds formed tend to vitrify and close the pores of the lime, thus preventing free access of water.

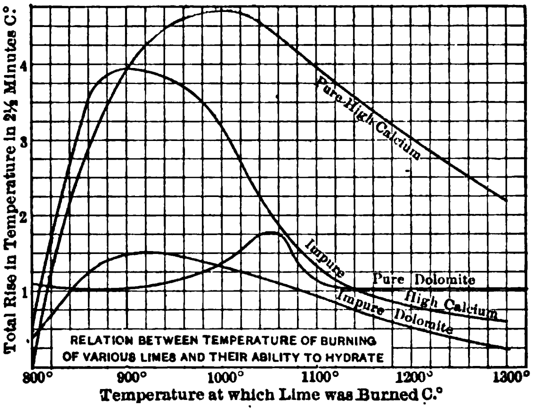

FIG. 15.

23. Setting and Hardening. Accompanying Phenomena. The setting of lime and lime mortar is a simple chemical process involving essentially only the evaporation of the large excess of water used in forming the lime paste, followed by the gradual replacement of the water of the hydroxide by carbon dioxide in the atmosphere, causing the lime hydrate to revert to the original calcium carbonate. Dry carbon dioxide will not react with dry hydrated lime, and it is therefore necessary that excess moisture be present.

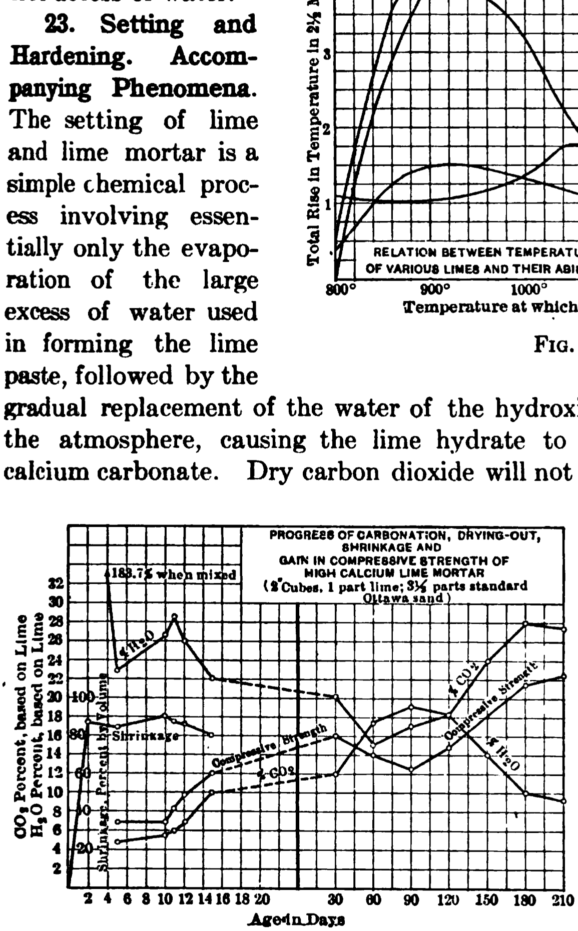

FIG. 16.

Recent studies made at the Bureau of Standards by Messrs. W. E. Emley and S. E. Young * have demonstrated the interesting fact that the loss of water during setting is not a continuous process, but that a reversal of the process occurs in the course of a week after mixing, and the percentage of water thereupon increases for several days or a week, after which it again decreases slowly. The data upon which this statement is based are presented by Figs. 16 and

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* Proc. Nat. Lime Manfr's. Assoc., 1913, pp. 254–267.

17. It will be noted that for both high-calcium and dolomitic lime mortars the loss of water during the first five or six days is extremely rapid, about 85 per cent of the water originally present having been lost during this interval. (It is probable that most of this water was lost by the end of the second day, since the shrinkage at that period is about the same as it is at the five- or six-day period.) Beginning about the fifth or sixth day (possibly still earlier), the moisture content and the shrinkage increase simultaneously until a certain period is reached (about eleven days for high-calcium, and fourteen days for the dolomitic lime), after which both decrease. This phenomenon was again investigated in two series of supplementary tests, one of neat lime, the other lime mortar containing 3½ parts of 200-mesh flint. Both corroborated the original work.

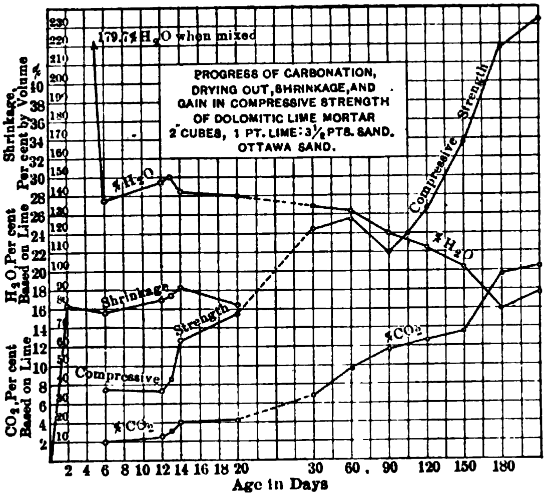

FIG. 17.

24. Plasticity. Sand-carrying Capacity and Yield. The term "plasticity" is commonly used to describe the quality of lime putty or mortar, not with a nice regard for the precise meaning of the term, i.e., capacity for being molded, but rather as a term descriptive of the spreading quality of the material when used in plastering. If it spreads easily and smoothly, it is plastic; if it sticks or drags under the trowel, or cracks, curls up, and drops behind the trowel, it is non-plastic or "short." The term "plasticity," used in this sense, is not equivalent to the term "viscosity," since the latter implies stickiness or, in the strict physical sense, an internal resistance to instantaneous change of form. Methods of experimental determination of plasticity, which amount simply to the subjection of the material to a test with some type of viscosimeter, do not therefore give results which have any direct bearing upon the applicability of the material as a plaster. The usual viscosimeter test, consisting in the measuring of the time or the force required to pull a plunger of given dimensions out of a paste of the material, shows a high-calcium lime to be much more viscous than a magnesian or dolomitic lime, whereas as a matter of common experience, the latter classes of limes produce mortars which work much more smoothly under the trowel, while high-calcium lime mortars are apt to be sticky and work " short."

The plasticity of a lime paste is dependent primarily upon some quality inherent in the dry lime. The presence of magnesia, for instance, as above noted, exerts a marked beneficial effect upon plasticity. The plasticity is also dependent upon the character of the reaction involved in slaking. It is believed, as explained above (Art. 22), that the plasticity is largely dependent upon the relative proportions of crystalline and colloidal hydroxide formed; that excess of the former causes grittiness; of the latter, stickiness.*

Practically all lime used structurally is made up in the form of a mortar by the addition of sand to lime paste. This circumstance is due not simply to the fact that sand is cheaper than lime, but also to the fact that the great shrinkage which accompanies the setting and hardening of lime putty can thus be diminished and the consequent cracking be in a measure prevented. The extreme stickiness of some high-calcium limes is also counteracted by the sand.

It is therefore absolutely necessary to dilute the lime with from two to four parts of sand to one of lime putty, and it becomes highly important that the " sand-carrying capacity " of the lime be properly established. If too little sand be used, excessive shrinkage will cause a weakening of bond between the plaster or mortar and the masonry materials or plastered surface, and when the bond is mechanically increased, as in the case of plaster spread upon lath, the openings between which provide a key for the mortar, shrinkage cracks inevitably appear. On the other hand, too much sand produces a non-plastic and weak mortar.

The sand-carrying capacity of a lime is expressed by the number of parts of sand which may be added to the lime without rendering the mortar too stiff to work well under the trowel. No scientific standard of plasticity has been generally adopted; therefore no fixed standard of sand-carrying capacity has been established. Common experience has shown, however, that pure high-calcium limes excel in sand-carrying capacity, impure high-calcium, and magnesian limes will carry less sand, and dolomitic limes carry least of all.

The volume of paste of a definite consistency which a given amount of lime will yield when slaked is a matter of great practical importance, since the amount of lime required to produce a given quantity of plaster or mortar is estimated therefrom. If a fat lime and a lean lime are slaked with equal proportions of water under the same conditions, the

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* Emley, Proceedings Nat. Lime Manfr's. Assoc., 1913, p. 77.

fat lime will produce a thick paste when the lean lime yields a thin milk. The fat lime is said to show the greatest " yield." The yield of a lime can only be expressed by the volume of paste of a stated consistency produced per unit weight of dry quicklime. Pure high-calcium limes yield the largest volume of paste per unit of weight, impure high-calcium and magnesian limes expand less upon being slaked and therefore show a lower yield, and dolomitic limes produce the smallest volume of paste of any class of quicklime.

The sand-carrying capacity and the yield of limes appear to be dependent upon the same qualities inherent in the lime as does the plasticity. The proportionate amounts of colloidal and crystalline hydroxide formed in slaking appear also to be intimately connected with these properties, both being increased if circumstances favor the formation of the colloidal hydrate.

25. Waste. The determination of the proportion of a sample of lime paste which cannot be washed through a 20-mesh sieve by a stream of water, i.e., the " waste," serves primarily as a check upon the proper carrying out of the various steps in manufacturing the material. It also serves to eliminate limes which are unfit for use in plasters, etc., unless the paste is screened before using.

The material which cannot be washed through the sieve consists of lumps of more or less foreign material which did not disintegrate when the lime was slaked. These lumps impair the working qualities of plaster, and, if they consist of overburned lime, they are apt to become hydrated and expand after the plaster sets, thus causing the " popping " or " pitting " which not infrequently disfigures the surface of plastered walls.

The presence of lumps of foreign material which do not slake and disintegrate is caused very largely by improper burning of the limestone, the temperature at which combination is effected with the impurities having been exceeded.*

The proposed specifications of the American Society for Testing Materials permit a maximum waste of 3 per cent for selected quicklime, and 5 per cent for run-of-kiln quicklime.

26. Hardness, Time of Setting, and Shrinkage. The hardness of lime mortar, meaning by the term " hardness " resistance to impact and abrasion, has an important bearing upon the suitability of the material for use in wall plasters. No method of testing the hardness of lime mortars has yet been standardized, however, and quantitative experimental data on the subject are therefore lacking. Comparative tests made upon various classes of limes, as well as the common experience of builders, have shown, however, that dolomitic limes produce the hardest

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* See discussion of this point in Art. 17, p. 23.

mortars, magnesian limes are less hard, and high-calcium limes least hard.

The time of setting of limes and mortars is most important in connection with the use of the material in plastering operations. Lime is naturally extremely slow setting, which circumstance necessitates waits of long duration between the application of the scratch coat and the brown coat. The slow-setting properties of lime, as much as any other one characteristic, have been responsible for the great inroads made during recent years by the quick-setting gypsum plasters in this field once occupied solely by lime.

The humidity and the degree of carbonation of the atmosphere influence the rate of setting of lime to a very large extent, drying the air and charging it with carbon dioxide, greatly accelerating the setting process.

An experimental method of determining the setting again has not been standardized, and the time of setting typical of various limes cannot therefore be given quantitatively. It is a fact well understood by practical masons, however, that magnesian limes are slower setting than high-calcium limes, and the dolomitic limes set still more slowly.

The decrease in volume or " shrinkage " of lime putty which accompanies the process of setting and hardening is directly accounted for by the volume of water lost, the net decrease in volume being slightly affected by an expansion entailed by the gain in carbon dioxide. As above noted, it is the universal practice to largely overcome the contraction and consequent cracking of mortars and plasters by the addition of several parts of sand to one of lime paste. The only exception to this rule is the fact that neat lime putty is sometimes used as a thin " skim " coat on plastered walls. In this case fine hair cracks do occur, but they penetrate to so slight a depth that they do not open up appreciably.

The amount of shrinkage shown by limes is not closely related to chemical composition, but all magnesian and dolomitic limes shrink less than do high-calcium limes. This circumstance constitutes one reason for preferring the former class of limes for the relatively rich mixtures used for the finish coat on plastered walls.

27. Crushing and Tensile Strength of Lime Mortars. In spite of the fact that lime has been used as a structural material since the earliest times only a very slight amount of investigational work has ever been done with a view to determining the strength of various limes and lime mortars. In consequence, very little data of dependable character are available as a source of definite information concerning the mechanical properties of this widely used material. Testing methods have not been standardized by our National Societies, as is the case with most other structural materials of equal importance, and the results of a portion of the few studies that have been made are rendered valueless for comparative purposes by reason of variations in essential details of investigational methods employed, or failure on the part of the investigator to recognize the importance of certain factors which exert a great influence upon test results.

The data quoted in this chapter are derived from only one source—a series of tests under the direction of Professor Ira H. Woolsen of Columbia University.* The tests were, for the most part, made in a manner closely approximating the standard method of testing Portland cement.

TENSILE STRENGTH, HIGH-CALCIUM AND DOLOMITIC LIME MORTARS

The tensile strength of lime mortars, both high-calcium and dolomitic, is represented by curves I and II of Figs. 18 and 19, which have been plotted from the data of the tests of Professor Woolsen above mentioned. Curve I represents the average strength values obtained in three tests of each of two brands of high-calcium lime. Curve II represents the average values obtained in three tests of one brand of dolomitic lime. The high-calcium limes contained, respectively, 94.0 and 95.5 per cent of CaO, less than 1.0 and 2.25 per cent of MgO, and 2.0 and 0.8 per cent of impurities other than H_2O and CO_2. The dolomitic lime contained 55.2 per cent of MgO, and 1.5 per cent of impurities.

The test specimens were briquettes having a minimum cross-section of 1 square inch, molded in the standard cement briquette mold. The lump lime was combined with the desired proportion of sand, slaked by the addition of the amount of water found necessary to produce a consistency such as is usually produced in practice, allowed to season for a period of twenty-four hours, and then packed in the molds. The specimens were removed from the molds as soon as sufficiently hard, and were stored in the basement of the laboratory throughout the period of aging. During the first two weeks the briquettes were subjected to immersion in water for a two-minute period each forty-eight hours. Thereafter, they were subjected to a three-minute immersion once each week. All specimens were thoroughly dry when tested.

The specimens used for the tests represented by the curves I and II, Fig. 18, were a mixture of one part by weight of lump lime to three parts

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* Published by E. W. Lazell in Proc. Am. Soc. for Test. Matrls., Vol. 10, 1910, pp. 328–340.

The author has averaged the tests of two brands of high-calcium mortars which were separately reported by the experimenter.

by weight of standard Ottawa sand.* Curves I and II, Fig. 19, represent tests of mixtures of one part by weight of lump lime to five parts by weight of standard sand.

An examination of the curves immediately impresses one with the fact that the dolomitic lime is immensely superior to the high-calcium lime in tensile strength. In the mortar of 1 : 3 mix, Fig. 18, the strength of the dolomitic lime mortar is practically double that of the high-calcium lime at all ages, and at one year averages 125 pounds per square inch, as compared with the 60 pounds per square inch shown by the high-calcium lime mortars. The same condition is evidenced no less strikingly by the tests of mortars of 1 : 5 mix, Fig. 19. In this case the average strength of the dolomitic lime mortar is 124 pounds per square inch at one year, as compared with 39 pounds per square inch for the high-calcium lime mortars.

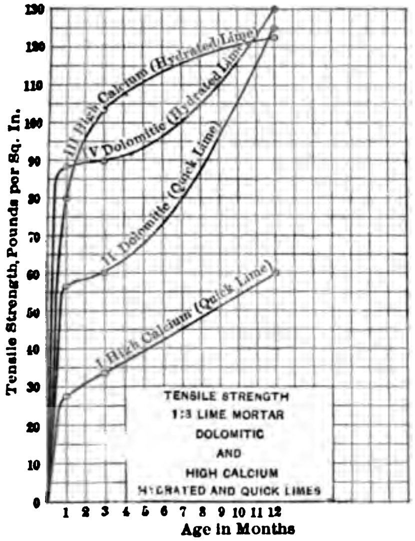

FIG. 18.

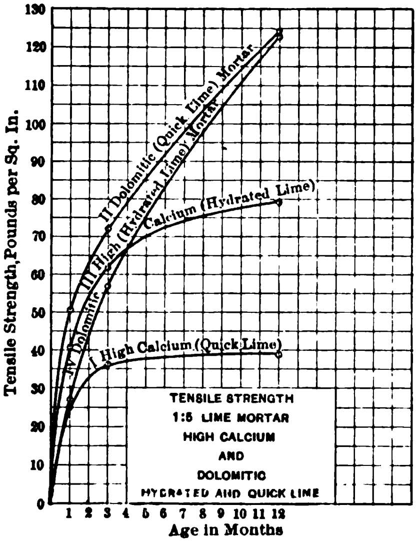

FIG. 19.

Comparing the relative sand-carrying capacities of the two classes of lime, using as a criterion the relative tensile strengths of the 1 : 3 and 1 : 5 mortars in each case,† we find that they are almost equally efficient except in the case of the strengths at one year, wherein the

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* See specifications for standard Ottawa sand, Chap. VII, p. 151.

† The term "sand-carrying capacity" is here used not in its strict proper sense, referring only to the working qualities of the mortar.

dolomitic lime far excels the high-calcium lime. (See also Fig. 23 and accompanying discussion.)

In concluding the discussion of these tests of tensile strength of lime mortars, attention is called to the fact that the number of different limes tested, as well as the number of specimens actually broken, is far too limited to afford reliable data as to the actual strength which a given lime mortar may be expected to develop at a given age. In fact, the tests herein averaged showed a great variability in strength of individual specimens of the same mortar. It is believed, however, that the facts emphasized as to relative strengths of high-calcium and dolomitic mortars are dependable and typical of practically all limes. This conclusion is supported by the fact that practically all tests of the two classes of limes, the results of which have been published, show about the same degree of superiority in tensile strength of dolomitic lines compared with that of high-calcium lime as is shown by the tests herein quoted.*

COMPRESSIVE STRENGTH, HIGH-CALCIUM AND DOLOMITIC LIME MORTARS

The compressive strength of the same specimens of mortars whose tensile strength is reported above is represented by curves I and II of Figs. 20 and 21. The compressive test specimens were half briquettes which had previously been broken in tension. The compressive strength values are doubtless somewhat higher than would have been obtained with cubical specimens, because the ratio of cross-sectional area to height was greater than it would be for cubes. However, it must be remembered that mortars are never subjected to compression except in situations where the bearing area is very great in comparison with the thickness of the mortar bed. It is fortunate, however, that the specimens were small, since the larger the specimens, the more imperfect will be the hardening in the interior. A further advantage in the use of half briquettes as compressive specimens, moreover, is the fact that a direct comparison between tensile and compressive strength of the same mortar is thereby afforded.

The striking feature of these curves is again the fact that the compressive strength of dolomitic lime mortar is practically double that of high-calcium lime mortar. In the 1 : 3 mix, Fig. 20, the dolomitic lime shows an average of 357 pounds per square inch at one year, compared with 232 pounds per square inch shown by the high-calcium lime; and in the 1 : 5 mix, Fig. 21, the corresponding figures are 528 pounds per

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* See Municipal Engineering, Vol. 28, p. 6; also Engineering News, Vol. 51, June 9, 1904, and Trans. Nat. Lime Manfr's. Assoc., 1913, pp. 77–103.

square inch for the dolomitic lime, and 251 pounds per square inch for the high-calcium.

The condition as to the relative sand-carrying capacity * of the two classes of limes, as measured by the relative compressive strengths of the 1 : 3 and 1 : 5 mortars, is practically identical with the condition found in the case of the tensile strength tests. In both instances the sand-carrying capacity of the dolomitic lime equals or exceeds that of the high-calcium lime. (See also Fig. 23 and accompanying discussion.)

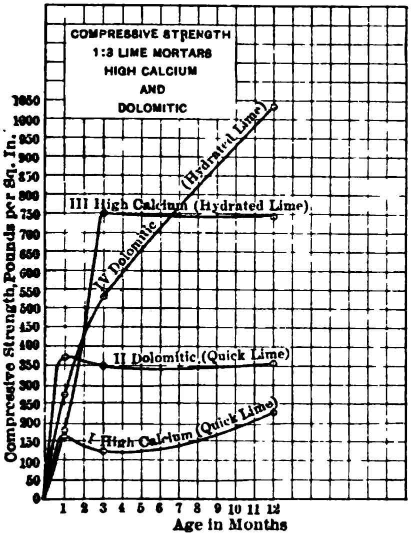

FIG. 20.

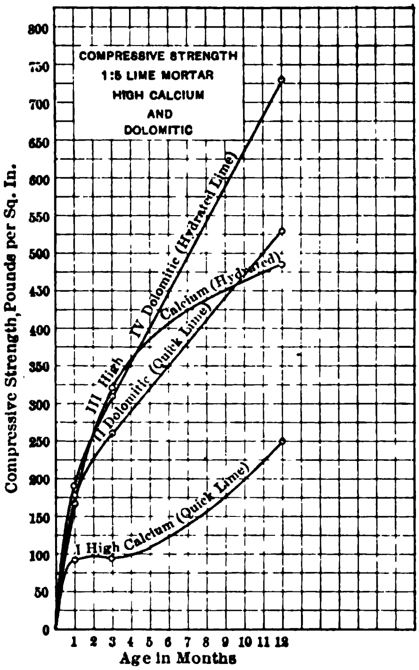

FIG. 21.

EFFECT OF IMPURITIES ON PROPERTIES

The principal impurities in limestones have been stated to be silica, iron oxide, and alumina, all of which may under certain conditions combine with lime and magnesia to form complex compounds which would profoundly affect the properties of lime if present in sufficient amounts. As a matter of fact, however, the maximum content of these constituents usually allowed in the finished lime is so small (not over 5 per cent) that their effect can never be very pronounced. In addition, the temperature attained in calcination is usually not sufficient to effect the formation

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* See footnote, p. 41.

of compounds of lime with silica, iron oxide, and alumina, and these latter constituents therefore exist unchanged in the calcined lime and exert no influence on strength other than as diluents.

The U. S. Bureau of Standards has made an incomplete study of the effect of various impurities upon the properties of lime, and while no definite report has been made, the following general conclusions have been drawn by Mr. Emley, Assistant Chemist: *

"The presence of small amounts of silica tends to decrease the plasticity, sand-carrying capacity, and yield of lime, but has no apparent effect upon its hardness or strength. The same may be said of iron, except that large amounts (25 per cent) show a marked increase in both strength and hardness. Alumina increases all the factors above mentioned and also improves the color, so that its presence even in large amounts is very desirable. On the contrary, gypsum shows detrimental effects even when only 1 per cent is present. Kaolin seems to act in a manner similar to silica and iron."

The actual import of the conclusion expressed by the investigator just quoted must not be exaggerated. It is not stated that the silica, or the iron, or the alumina content of commercial limes is under any circumstances a large factor in strength or other mechanical properties of that lime; it is simply stated that when quantities of these substances far exceeding the limits of possible composition of ordinary limes are combined with lime, the effect upon mechanical properties is a very notable one. When these adulterants are present in such proportions, indeed, we no longer have an ordinary lime to consider, but instead a very different material which partakes of the nature of the hydraulic limes and cements, which owe their superior mechanical properties solely to their comparatively large content of argillaceous materials, the very constituents whose influence upon lines we are now discussing—the silica, the iron oxide and the alumina.† Finally, it must be stated that, whatever the extent of the contamination of the lime by these argillaceous materials, the latter would not be materially effective in so far as increasing the strength of the lime is concerned, were not the calcination temperature considerably higher than that necessary for proper calcination of the lime. This circumstance explains the fact that it is not easy to overburn a very pure limestone, but an impure limestone may be overburned because a temperature is attained at which combination is effected between lime and silica and iron oxide and alumina, the resulting com-

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* Technologic Paper No. 16, Bureau of Standards, Feb. 1913.

† The compounds formed by these constituents in hydraulic cements are inert, just as they are in hard-burned lime, until the clinker formed in burning is pulverized to an impalpably fine powder.

pounds being of such a nature that they greatly impair the ability to slake, the quick-setting properties, and the strength of the lime, as above noted.

EFFECT OF TEMPERATURE OF CALCINATION

The temperature of calcination affects the properties of lime to a marked degree, as has been noted in Arts. 22 and 25 above. It may be so low that dissociation of the carbonates is incomplete on the one hand, causing loss of power to hydrate, or so high that the combination of the lime with the impurities is effected on the other hand, again causing loss of power to hydrate and also causing an increase in the waste. In the first event the lime is under-burned, in the second it is over-burned, and as has been shown, overburning is practically impossible unless the limestone contains impurities. Both the overburned and underburned material can easily be recognized in the kiln product, moreover, and should be sorted out before the lime is marketed. The underburned material can be recalcined, but the overburned material must be thrown away.

It appears, therefore, that (provided the lump lime is properly sorted) the only effect of improper regulation of calcination temperatures is loss of manufacturing efficiency. It is to the interest of the manufacturer to so burn the limestone as to obtain a maximum amount of marketable lime, but the engineer or architect who uses the lime is not concerned beyond the point of being sure that the underburned or overburned material has been rejected by the manufacturer.

EFFECT OF METHOD OF SLAKING

The statement has often been made that lime slaked, as is usually the case on construction work, by the use of a large excess of water, will produce a mortar of lower strength than the same lime slaked with little or no excess of water. It appears, however, that this statement may be an error, due perhaps to the fact that an increased amount of water used in slaking is apt to mean an increased percentage of water in mortar mixtures. In any event it is an undoubted fact that, under the conditions of slaking and mixing which usually obtain on construction work, it is far safer to instruct the mason's tender to use such an excess of water as to produce a plastic putty or even a paste, thus practically eliminating the possibility of incomplete hydration, than to attempt to secure a physically dry hydrate or even one containing only a small excess of water through the instrumentality of an unskilled laborer.

An investigation of the effect of various methods of slaking made by Mr. H. Burchartz * resulted as follows, the tests being made upon a lime-sand mortar of 1 : 3 mix at the age of one year:

Method of Slaking.	Compressive Strength.	
	Kg. per Sq.cm.	Lbs. per Sq.in.
Water added all at once, no stirring	26.0	370
Water added a little at a time, constant stirring	28.1	400
Slaked with large excess of water	32.1	457

EFFECT OF CHARACTER OF SAND

The influence of the size of the sand grains upon the strength of lime mortars is illustrated by Fig. 22, which represents the results obtained in tests of mortars made at the Bureau of Standards by Mr. W. E. Emley and Mr. S. E. Young.† The specimens used in these tests were 2-inch cubes, ninety days old, containing 1 part by weight of quicklime to 3½ parts sand. Run-of-bank Ottawa sand was obtained and separated by screening into 4 sizes: 20–40, 30–40, 40–60, and 60–80 mesh. A Merrimac River sand was also obtained and screened to procure a sand of 10–20 mesh size. The curves represent the average of five tests of each mortar for each class of lime.

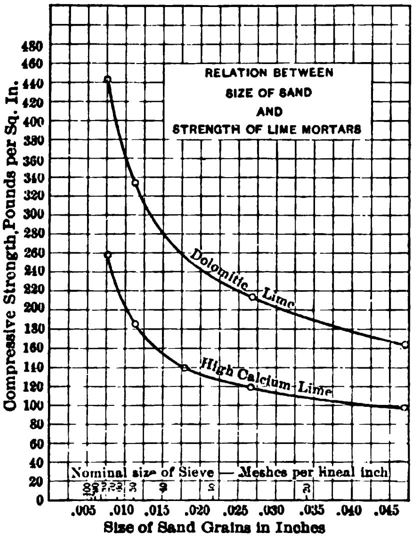

FIG. 22.

It will be noted that by far the strongest mortars are produced by the fine sand, the compressive strength being roughly an hyperbolic function of the average diameter of the sand grains.

These results substantiate the generally accepted belief that fine sand is best for lime mortars, and should be especially noted in view of the fact

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* Luftkalke und Luftkalk-mörtel.

† Proc. Nat. Manfr's. Assoc., 1913, pp. 254–257.

that coarse sand or sand of a composition well graded from fine to coarse has been shown to yield the strongest mortars in the case of both natural and Portland cements.

Effect of Size of Test Specimens

The setting and hardening of lime mortars has been explained as a process of gradual replacement of the water of hydration by carbon dioxide in the atmosphere. Since the successful accomplishment of the process is dependent upon the action of the air, the hardening process begins at the surface of the exposed mortar and proceeds inward very slowly. (Emley * found that a 6-inch cube, the outermost portion of which possessed 17.5 per cent of CO_2 and 19.8 per cent of H_2O after nine months, possessed 1.2 per cent of CO_2 and 31.1 per cent of H_2O, at the center, showing that setting and hardening had scarcely begun 3 inches below the surface.) The gain in mechanical strength parallels the gain in hardness, and the average unit strength of a specimen of large cross-sectional dimensions at a given age will therefore never equal that of a smaller or thinner specimen in which the ratio of exposed surface to volume is greater.

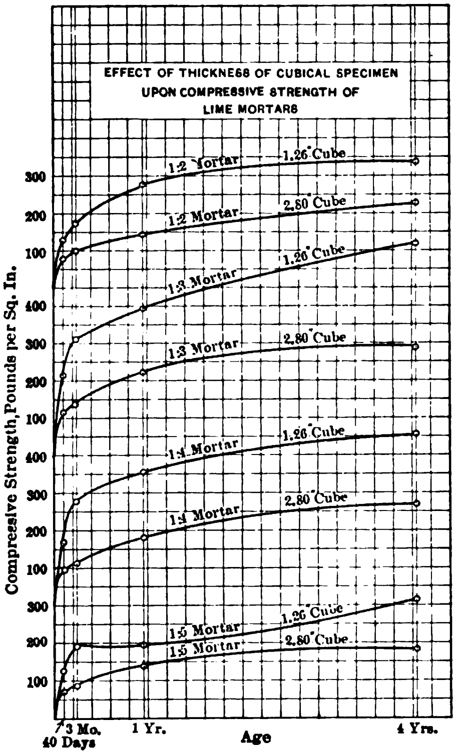

Fig. 23.

This fact is forcibly illustrated by the curves of Fig. 23, which have been plotted from the data of a series of tests made by Mr. M. Gary.† The various mortar mixtures were made from high-calcium lime and a natural sand. Slaking, mixing, and molding were done by hand; all specimens were cubical, either 1.26 inches or 2.80 inches on a side; the

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* Loc. cit., p. 259.

† M. Gary, Erhärtung von Kalkmörteln. "Bau Materialienkunde," Vol. 5, 1900, pp. 216–217.

slaked lime was seasoned one week before molding, and all specimens were stored in air. Each curve is the average of about four compressive tests at each age.

A remarkably constant relation is shown for all mortar mixtures between the strength of the small cubes and that of the larger cubes, that of the latter always amounting to from 40 to 70 per cent (usually about 50 to 60 per cent) of that of the former. It is interesting to note further that the relation is nearly constant at all ages except that the proportionate gain in strength of the larger cubes between the ages of one and three months is less than it is at other periods.

28. Relative Applicability of Various Limes to Special Uses. High-calcium, magnesium, and dolomitic limes each possess certain special advantages as building materials. Strong preferences exist among plasterers and masons, but these preferences are not always well founded and are not the same in different sections of the country. In the following enumeration of the principal structural uses of limes an effort has been made to indicate the special reasons why one class of lime may be superior to another for the purpose indicated. The limitations of each lime cannot be defined by hard-and-fast rules, however, and divergence from the practices noted will doubtless be frequently encountered on construction work.

Plasters. The plasterer has usually a strong preference for magnesian or even dolomitic limes for both the " scratch " coat, the " brown " coat, and the finish, or " skim " coat, on plastered walls. This is due to the fact that these classes of limes work much more smoothly under the trowel than do high-calcium limes, and also to the fact that the more slowly setting properties of these limes make it possible for him to spread a larger surface in one operation before stopping to complete the surface treatment. (Leveling up and then roughening with a brush or scratching with a trowel or other implement, in the case of the first coat, and using the float to produce a smooth surface in the case of the brown coat and the finishing coat.) Another advantage of magnesian and dolomitic limes is the lessened danger of the development of " lime-pops " caused by the late hydration of small particles of lime. The increased hardness of the wall surface secured with dolomitic limes is also usually considered an advantage.

One possible additional reason for the preference felt by the plasterer for magnesian or dolomitic limes is the fact that he is usually given a richer mortar than he would be given if high-calcium lime were used. This is due to the fact that magnesian limes will not carry as much sand as high-calcium limes and the temptation for the mason's tender to turn out a too heavily sanded mixture is not so great.

Mortar for Ordinary Brick Masonry. The bricklayer usually prefers the magnesian or dolomitic lime mortar for the same reason that the plasterers do, i.e., its more slowly setting properties and greater plasticity make it possible for him to spread with less effort a greater surface with mortar, and he is consequently able to lay a greater number of bricks in one operation.

The cooler limes are also preferred because of the lessened danger of encountering an irregular and lumpy mortar caused by unskillful slaking and consequent burning of high-calcium lime mortar.

Mortar for Face Brick. Dolomitic lime is invariably preferred for laying dry-pressed or face brick. This class of bricks is commonly laid with joints not exceeding ⅛ inch in thickness, and it is absolutely necessary that the mortar be very plastic and very slow setting in order that such thin joints may be secured, and the bricks at the same time be accurately placed in proper alignment.

Mortar for Stone Masonry. High-calcium lime mortars are usually preferred by the stone mason because of their more quickly setting properties, which constitute a distinct advantage. They become stiff enough to carry the load put upon them without deformation in a very short time, thus facilitating the proper setting of heavy stones.

29. Production, Value and Uses of Lime. Statistics of the lime industry are presented in the table below. These data have been abstracted from the reports of the U. S. Geological Survey, published annually in "Mineral Resources of the United States."

STATISTICS OF LIME INDUSTRY

Year.	1910.		1911.		1912.		1913.	
No. plants operating.	(1125)		(1139)		(1017)		(1023)	
Use.	Quantity, Short Tons.	Value per Ton.	Quantity, Short Tons.	Value per Ton.	Quantity, Short Tons.	Value per Ton.	Quantity, Short Tons.	Value per Ton.
Building lime	1,722,488	$4.26	1,488,567	$4.54	1,556,446	$4.22	1,358,099	$4.43
Chemical works	182,043	3.82	256,215	3.65	282,984	3.50	388,369	3.45
Paper mills	286,922	3.76	286,485	3.87	290,347	3.81	284,090	4.18
Sugar factories	29,421	8.14	36,424	6.65	30,988	6.01	32,236	6.72
Tanneries	28,921	4.62	30,167	4.59	40,595	4.40	49,591	4.38
Fertilizer	585,876	2.93	596,664	2.87	604,607	3.06	590,229	3.05
Dealers, uses not stated	496,930	4.27	531,249	4.15	560,186	4.40	692,265	4.56
Other uses *	149,179	3.70	167,144	3.55	157,843	3.79	200,511	3.61
Total	3,481,780	3.99	3,392,915	4.03	3,529,462	3.96	3,595,390	4.97

* Includes lime for sand-lime brick, slag cement, alkali works, steel works, glass works, smelters, sheep dipping, disinfectant, manufacture of soap, cyanide plants, glue factories, purification of water, etc.

CHAPTER III

HYDRATED LIME

30. Definition. " Hydrated lime " is that article of commerce which is produced by the hydration, at the place of manufacture, of ordinary quicklime, the process being so conducted that excess water is largely evaporated by the heat generated, and resulting in the production of a physically dry powder from which impurities or lime existing in the anhydrous form may be removed by air separation or screening.*

31. Process of Manufacture. Three stages of manufacture characterize all processes of preparation of hydrated lime, whether patented or not. These are:

(1) The lump quicklime must be crushed to a fairly small size.

(2) The crushed material must be thoroughly mixed with a sufficient quantity of water.

(3) The slaked lime must, by air separation, screening, or otherwise, be separated from lumps of unhydrated lime and impurities, or the entire mass must be finely pulverized, thus leaving the material which made up the lumps in the finished product.

Crushing. The degree of crushing employed at various hydrated lime plants varies greatly. In some plants the quicklime is simply crushed to a 1-inch size; in others, and this is the more common practice, the quicklime is crushed in a pot or Sturtevant crusher to a size of ½ inch or under. A few plants, after crushing the quicklime, pulverize it so that the greater portion will pass a 50-mesh sieve.

Mixing with Water. A great number of processes, and several distinct types of machines are used for hydrating quicklime. The only two methods extensively used, however, are the batch process, using a machine of which the Clyde hydrator is typical, and the continuous process, in which a machine of which the Kritzer hydrator is typical

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* The proposed standard specifications of the Am. Soc. for Test. Mat. define hydrated lime simply as "a dry flocculent powder resulting from the hydration of quicklime."

is used. Either process may give entire satisfaction providing only that the plant operation is properly supervised and the character of the product kept under strict chemical control.

The Clyde batch process hydrator (Fig. 24), is a batch machine in which a given quantity of quicklime (usually 1 ton) is placed, and the proper quantity of water added by means of a spray. The machine itself consists of a revolving pan provided with plows, arranged in a horizontal spiral, which stir up and mix the water and lime. The water is weighed and added in a predetermined amount. The hydrated lime is scraped from the pan through an opening in the center into a hopper below the hydrator.

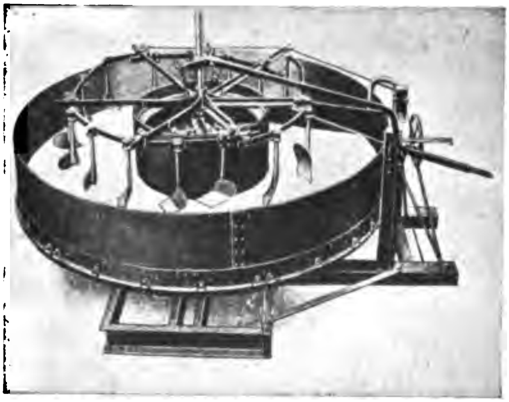

FIG. 24.—Clyde Hydrator.

The Kritzer continuous process hydrator (Fig. 25), consists of a number of cylinders, arranged one above the other, which are provided with screw-conveyors revolving around a central shaft. The quicklime is fed into the upper cylinder in a continuous stream and here water is sprayed upon it, the amount being regulated by valves. The moist lime is gradually worked by the conveyors through the upper cylinder into the lower ones, and by the time it is discharged from the lowest cylinder it is entirely hydrated. The spray of water is admitted through a stack located near the point of entrance of the lime to the upper cylinder. This stack serves as an outlet for both the dust and the steam which are unavoidable incidental products of the process of hydration. The water descending over a series of baffle plates in the stack absorbs the dust and condenses the steam. It therefore returns the dust to the hydrator and enters the upper cylinder of the hydrator hot. The advantages claimed for this type of hydrator over the batch machine, especially for treatment of hot limes, are those accruing from the introduction of water already hot, and the introduction of both quicklime and water in small constantly flowing streams, thus affording an opportunity for rapid and thorough mixing. On the other hand, the possibility of accurately gauging the proportions of water and quicklime is a great advantage claimed for the batch type of hydrator.

Removal of Lumps of Unhydrated Material. Owing to the increase in volume which accompanies slaking, the lumps of lime fall into powder during the process. Any impurities in the lime will not slake, however, and therefore will remain with any imperfectly hydrated lime as lumps which can be removed from the finished product by screening or by other means such as the method of air separation now commonly used.

The form of screen usually employed consists of a wire netting stretched on an inclined frame which is mechanically agitated as the material traverses its length. The usual size of the mesh is from 35 to 50 meshes per linear inch. The whole structure must be enclosed to keep the dust in.

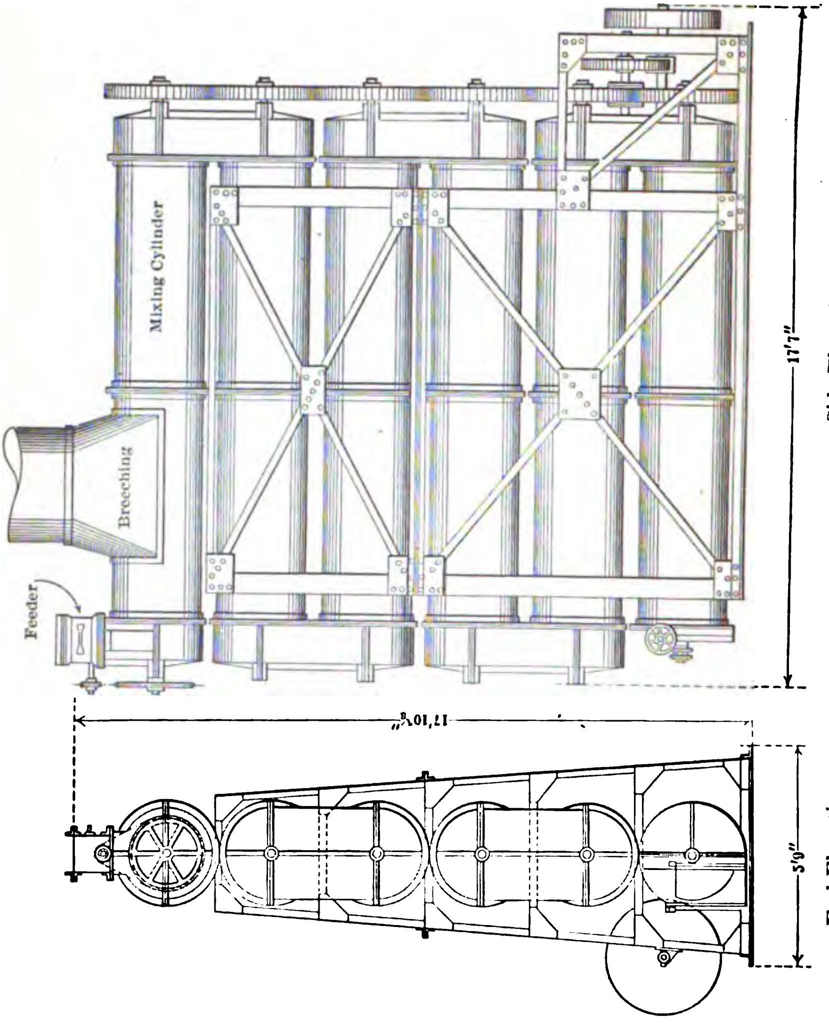

FIG. 25.—The Kritzer Continuous Hydrator.

Air separation systems usually involve the use of a Raymond impact mill or similar device in which the hydrate is subjected to the heating action of rapidly revolving blades. The material thereupon encounters a current of air by which the fine material is carried off in suspension, while the larger particles settle out. The fine material is subsequently deposited in a chamber provided for the purpose in the air duct, the precipitation being effected by the reduction in velocity of the air current caused by the enlargement of the air duct. The air circuit is a closed one, the same air being used over again, and it is therefore a dust-proof device. A regulation of the size of the particles retained is very easily attained by merely varying the velocity of the air current through the speed control of the fan. A certain few hydrates, especially those which are offered on the market as finishing limes, are not subjected to either screening or air separation, but are pulverized just as they come from the hydrator in a Fuller mill or Bonnot mill. By this method the imperfectly hydrated lime, impurities, etc., find their way into the finished product.

The tailings from the screen, or material rejected by the air separator, usually contain a considerable proportion of unslaked lime. It is therefore possible to regrind this material and market it as agricultural lime.

Hydrated lime is usually packed in burlap or duck bags containing 100 pounds, or in paper bags containing 40 pounds.

32. Properties and Uses. Hydrated lime and ordinary lime which has been properly slaked on the work are, of course, exactly the same material, and therefore should have identical physical properties. As a matter of fact, however, the usual experience has been that stronger and more quickly setting mortars, and ones which shrink less upon setting and hardening, are derived from hydrated limes than from ordinary quicklime. On the other hand, mortars prepared from hydrates are vastly inferior to those prepared from quicklimes from the standpoint of plasticity, sand-carrying capacity and yield, except in the comparatively rare instances in which the hydrated lime paste is allowed a period of seasoning before being used.

The tensile strength of hydrated lime mortars, both high-calcium and dolomitic, is represented by curves III and IV of Figs. 18 and 19, previously referred to in Art. 27. The mortars whose properties are represented by these curves are made from precisely the same limes as those represented by curves I and II of the same figures, the only difference being that in the one case ordinary lump lime was hydrated by the experimenter, in the other the lime was procured from the same manufacturer in the hydrated form.

The proportions used for the test of Fig. 18 were 1 part by weight of hydrated lime to 3 parts by weight of Ottawa sand, and for the tests of Fig. 19, 1 part by weight of hydrated lime to 5 parts by weight of sand. The test specimens of hydrated lime mortar therefore contained a relatively lower percentage of CaO than did the corresponding specimens made from quicklime, since a considerable amount of chemically combined water was included in the weight of the hydrated lime.

A comparison of curves III and IV of both Figs. 18 and 19 shows a certain degree of superiority of dolomitic hydrated lime mortar over high-calcium hydrated lime mortar at most ages, the advantage of the former becoming apparent only after the expiration of several months, however, and being more pronounced in the case of 1 : 5 mortar than in the 1 : 3 mortar.

Curves I and III, also curves II and IV of these figures afford a direct comparison between the tensile strengths of the hydrated lime mortars and the corresponding quicklime mortars. The following conclusions appear to be warranted by the test results:

> (*a*) High-calcium hydrated lime mortar is about 100 per cent stronger in tension than the corresponding quicklime mortar;
>
> (*b*) Dolomotic hydrated lime mortar and dolomitic quicklime mortar appear not to differ materially in tensile strength except at early ages, and the great superiority of the hydrate noted in the case of high-calcium limes appears not to be characteristic of the dolomitic limes at any age or for any mix. This condition in a measure supports the belief that the superiority of hydrated lime mortars is largely due to the more perfect hydration. Naturally this factor would be less operative in the case of the dolomitic limes, whose hydration is attended with far less difficulty than in the case with high-calcium limes.

The compressive strength of the same specimens of hydrated lime mortars is represented by curves III and IV of Figs. 20 and 21; a comparison of curves III and IV in each case reveals the same situation as to the relative compressive strengths of high-calcium and dolomitic lime mortars as has been noted in the discussion of tensile strength. The dolomitic limes show a less rapid early gain in strength, but ultimately surpass the high-calcium limes by a considerable amount.

Comparing the relative compressive strengths of the hydrated lime mortars and the corresponding quicklime mortars (curve I vs. curve III, also curve II vs. curve IV in each case), the following conclusions may be again drawn:

> (*a*) High-calcium hydrated lime mortar is from 100 to 200 per cent stronger in compression than the corresponding quicklime mortar:
>
> (*b*) Dolomitic hydrated lime mortar is considerably stronger in compression than the corresponding quicklime mortar, but the superiority of the former is usually less marked than in the case of the high-calcium limes.

33. Hydrated Lime vs. Quicklime. The superiority of hydrated lime over the ordinary lump lime from the standpoint of the mortar strength developed has been indicated in the preceding article. The advantage accruing from the use of a material which need only be mixed with water, instead of being slaked upon the work with the attendant danger of burning or incomplete hydration, has also been noted above. There remain, however, certain advantages and disadvantages to be derived from the use of the commercial hydrate which will be considered briefly.

Hydrated lime can be more conveniently handled than lump lime because of its powdered condition, and can safely be stored or shipped by rail or water in cloth or paper bags or even in bulk. On the other hand lump lime deteriorates rapidly in storage or transportation, through air-slaking, is considered an unsafe commodity to carry by water, and wherever kept always constitutes a fire hazard.

Ground quicklime could be handled in much the same way as is hydrated lime, and perhaps would be so handled were the fact generally recognized that the extent of air slaking is dependent largely upon the fineness of the material and consequent accessibility to the action of the air, rather than upon the quality inherent in the quicklime or in the hydrate. A prejudice against ground lime, founded upon its resemblance to air-slaked lime, is still operative, however, in reducing its use as a structural material.

One property of hydrated lime which often constitutes an advantage on construction work is the fact that it is ready to be immediately incorporated with sand and water to form mortar, whereas ordinary lime must be allowed to season for from one day to several weeks after being slaked, thus probably causing delay.

The fact that hydrated lime is a physically dry material is an advantage in mixing mortars. The dry hydrate can be mixed with sand much more easily than can a lime paste or putty, and a more thoroughly homogeneous mixture is obtained before the excess water is added to make a plastic mortar.

On the other hand, mortars prepared from hydrated lime are very "short" and non-plastic, the volume of lime paste derived, i.e., the yield, is small, as compared with that obtainable from quicklimes, and the sand-carrying capacity is low. The lack of plasticity of lime hydrate mortars is alone sufficient to condemn the material from the standpoint of the practical mason and plasterer. Some hydrates are, indeed, so lacking in colloidal properties that they are absolutely gritty. As a result there is almost no market for hydrated lime as a plastering or finishing lime, with the exception of certain hydrates of special character which are produced in one district of limited extent.

The greatest value of hydrated lime as a structural material is as an ingredient of natural and Portland cement mortars and concretes. So used, it effects marked improvement in quality, especially in that greater plasticity characterizes the wet mixture. Mortars and concretes in which a small proportion of hydrated lime has been incorporated are also improved from the standpoint of impermeability and homogeneity of structure. The use of hydrated lime in combination with cements will be discussed in the chapters devoted to the properties and uses of natural and Portland cement.

34. Special High Alumina Hydrated Lime. The unsatisfactoriness of hydrated lime as a plastering material on account of the non-plastic, poor working mortars formed, and the slowness with which plastered walls dry out and harden, has led to many attempts to so modify the characteristics of the material as to correct these defects and enable it to compete with gypsum plasters as an easily applied, ready-to-use wall plaster.

These efforts have been far from uniformly successful, but, in at least one instance, a material has been produced whose performances have made a very favorable impression upon the architect, builders, and artisans, and the material has come to be a fairly well-known article of commerce.

This product, marketed under the trade name "Alca Lime," is made by the incorporation with selected hydrated lime of about 15 per cent of a patented calcium aluminate compound which is derived as a slag from a blast furnace. This compound is not a normal blast furnace slag, but is derived from a furnace whose charge is so regulated that a slag high in alumina and relatively low in silica is produced. Its composition is about 25 to 35 per cent alumina, 20 per cent silica, and 35 to 40 per cent lime and magnesia. The slag is granulated by running the molten material into water or by causing it to encounter a jet of steam or water, and the material is subsequently ground to such a degree of fineness that not more than about 25 per cent will be retained on a 200-mesh sieve.

The lime manufacturer secures this material in a pulverized condition (from a proprietary company which holds the patents) and mixes it with his finished hydrated lime. An ordinary mixer is often used, but greater uniformity of composition is attainable if the two materials are together passed through a mill designed for fine pulverization of cement and other similar materials. Hair is subsequently added to the mixture in case it is intended to be used as a first plaster or stucco coat upon lath. Otherwise it is marketed without an admixture of hair.

35. Properties and Uses of High Alumina Lime. The physical and mechanical properties of Alca lime have been little investigated by parties other than those directly interested in the production of the material. In the absence of authentic published results of tests, therefore, the discussion of the properties of the material will be confined to a consideration of its performances in use, as noted by observers who have had experience with it on actual construction work. The fact should not be overlooked in this connection that this practical test must ultimately fix the place which any material shall come to hold as a material of construction.

Alca lime, considered from the point of view of the physical chemist, is a distinctly different material from ordinary hydrated lime, and partakes in a measure of the nature of the hydraulic limes and puzzolan cements considered in the chapters which follow. Its setting is not wholly a process of replacement of the water of the hydrate by carbon dioxide, but is a complex and not perfectly understood phenomenon in which the aluminate present plays an important part. Reasoning from the partial analogy to the constitution of Portland cement, it appears probable that the initial setting is due to the hydration of the aluminate, resulting in the formation of amorphous hydrated tricalcium aluminate, and possibly amorphous hydrated alumina. These amorphous compounds tend to render the mixture more plastic than is a mixture of water with hydrated lime alone, because of the fact that the dry-slaked hydrate is in part at least in a crystalline form, which causes it to " work short." The presence of the amorphous hydrate may also have a tendency to cause the crystalline lime hydrate to change over to the amorphous hydrated form, with consequent improvement in plasticity. The amorphous hydrated aluminate may possibly crystallize during the subsequent period of hardening, but there appears to be no good reason for believing that the hardening of the material is not due almost wholly to the recarbonation of the lime, as in the case of ordinary limes.

Alca lime comes upon the work ready to be mixed with sand and water and be used almost immediately. Best results are obtained if the sand and lime are first mixed dry, then combined with about 16 per cent of water, thoroughly mixed, and allowed to stand for not less than one hour before being used. Where conditions permit allowing the mix to stand overnight, an advantage is gained by so doing in that a very smooth working plastic mortar is thus derived.

Alca lime has given satisfaction as an interior plastering material used on wood or metal lath, terra cotta, or brick, and as a mortar material for laying brick or stone masonry. For use as the first coat of plaster or stucco it may be obtained from the manufacturer already mixed with hair. The brown coat of plastered walls should be applied before the scratch coat is quite dry, and an interval or two or three days in good drying weather allowed before the finish coat is applied. The material has excellent sand-carrying capacity, proportions of 1 part by weight of Alca to 3 or 3½ parts by weight of sand being recommended for first-coat work on wood or metal lath, and 1 part Alca to 5 parts sand by weight for first or second coats on brick, terra cotta, stone, etc. For second-coat work on lath 4 or 4½ parts by weight of sand may be used with 1 part of lime. Alca lime may also be used as a skim coat except where a pure white finish is required, its color being a gray-white.

Alca-lime plasters are well liked by the mason, who finds their working qualities to be equaled only by well-seasoned lump-lime plasters. Probably no other plastering material is so well adapted for all sorts of construction work—interior plastering, outside stucco, and mortar for brick, terra cotta, or stone masonry. It is also used in combination with Portland or natural cement, with all the advantages which accrue from the similar use of ordinary hydrated lime. So used it may in fact excel hydrated lime by still further improving the working qualities of the mortar and rendering it still denser, thus tending to produce a very impervious mortar or concrete.

36. Production, Value and Uses of Hydrated Lime. The uses of hydrated lime structurally and in various arts and industries have been indicated in the discussion of the uses of ordinary lime in Chapter II. No statistics are available as to the amount of hydrated lime used for various individual purposes, but the amounts so used have been included in the individual items and the totals given in the table at the end of Chapter II. The production and the average value of the total amount of hydrated lime used for all purposes in the United States are indicated by the following data abstracted from " Mineral Resources of the United States."

STATISTICS OF HYDRATED LIME INDUSTRY

Year.	1910.		1911.		1912.		1913.	
	Quantity, Short Tons.	Value per Ton.	Quantity, Short Tons.	Value per Ton.	Quantity, Short Tons.	Value per Ton.	Quantity, Short Tons.	Value per Ton.
	320,819	$4.02	304,593	$4.50	416,890	$4.39	493,269	$4.47

CHAPTER IV

HYDRAULIC LIME AND GRAPPIER CEMENTS

HYDRAULIC CEMENTING MATERIALS IN GENERAL

37. Introductory. The cementing materials heretofore considered have all belonged to the class of non-hydraulic cementing materials; all have been very simple both in composition and chemical action. The hydraulic cementing materials, however, comprise a class of products of very complex and somewhat variable composition and constitution, products, moreover, whose physical characteristics are not definitely fixed by chemical composition, and whose actual constitution is still imperfectly understood.

These materials all possess in common one property known as " hydraulicity," i.e., the ability to set and harden under water. In composition they agree to the extent that they all consist essentially of lime, silica, and alumina, or of lime and magnesia, silica, and alumina and iron oxide (i.e., magnesia may replace a part of the lime, and iron oxide a part of the alumina). The hydraulic cementing materials include hydraulic limes, grappier cements, puzzolan cements, natural cements, and Portland cements.

38. Classification of Hydraulic Cementing Materials. The Hydraulic Index and the Cementation Index. The degree to which the property of hydraulicity is developed by limes and cements is dependent almost wholly upon the character of the compounds of lime and magnesia with silica, alumina, and iron formed during manufacture. The chemical composition of the raw materials and the details of the manufacturing processes are influential factors, but are operative, in an indirect manner, only in so far as they affect the ultimate constitution of the finished product.

Formerly it was considered possible to classify cements accurately according to their relative hydraulicity by the use of a criterion called the " hydraulic index," which is simply the ratio of silica and alumina to lime, expressed as follows:

$$\text{Hydraulic index} = \frac{\text{per cent silica} + \text{per cent alumina}}{\text{per cent lime}}.$$

The values obtained by the use of this formula permit the tabulation of limes and cements by their hydraulic indices as follows: *

Hydraulic Index.	Product.
0.00–0.10	common lime.
0.10–0.20	feebly hydraulic lime.
0.20–0.40	eminently hydraulic lime.
0.40–0.60	Portland cement.
0.60–1.50	natural cements.
1.50–3.00	weak natural cements.
3.00	puzzolans.

This attempt to devise a formula which express in scientific terms the relative hydraulic values of limes and cements has been unsuccessful, primarily because it fails to take account of the character of the compounds formed during manufacture, i.e., the constitution of the product, and secondarily because it assumes silica and alumina to be quantitatively equivalent in chemical action and fails entirely to take account of the action of both magnesia and iron oxide. (See discussion of constitution of cement, Art. 106.)

Eckel has made an effort to avoid the deficiences and errors involved in the hydraulic index by the proposal of a new criterion of hydraulicity which he terms the "cementation index." The new rule proposed is based upon the assumption that the essential constituents of hydraulic cementing materials are:

Tricalcium silicate, $3CaO, SiO_2$;
Trimagnesium silicate, $3MgO, SiO_2$;
Dicalcium aluminate, $2CaO, Al_2O_3$;
Dimagnesium aluminate, $2MgO, Al_2O_3$;
Dicalcium ferrite, $2CaO, Fe_2O_3$;
Dimagnesium ferrite, $2MgO, Fe_2O_3$.

This assumption is primarily based upon the conclusion previously announced by S. B. and W. B. Newberry, as the result of extensive synthetic investigations of the constitution of Portland cement, that the essential constituents of cement are tricalcium silicate, $3CaO, SiO_2$, and the dicalcium aluminate, $2CaO, Al_2O_3$. Eckel has extended the application of the Newberrys' conclusions by assuming "that magnesia is, molecule for molecule, equivalent to lime in its action" and "that iron oxide is, molecule for molecule, equivalent to alumina."

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* Eckel, "Cements, Limes and Plasters," p. 169.

Taking into account relative weights, the ratio of the lime to each of the other constituents will be expressed as follows:

$$3CaO \div SiO_2 = 3(56.1) \div (60.3) = 2.8$$

$$2CaO \div Al_2O_3 = 2(56.1) \div (102.2) = 1.1$$

$$2CaO \div Fe_2O_3 = 2(56.1) \div (159.7) = 0.7$$

$$CaO \div MgO = (56.1) \div (40.3) = 1.4$$

and the form of the cementation index is:

$$\frac{2.8(\%SiO_2) + 1.1(\%Al_2O_3) + 0.7(\%Fe_2O_3)}{\%CaO + 1.4(\%MgO)} = 1.$$

If the value of the cementation index falls below 1.0, the cement must necessarily contain free lime or magnesia; when it rises above 1.0 the lime-magnesia content is lower than the theoretical maximum.

If the cementation index be used in classifying the various hydraulic cementing materials, the ranking of the latter according to hydraulicity is as follows:

Cementation Index.	Product.
0.00–0.30	common lime.
0.30–0.70	feebly hydraulic lime.
0.70–1.10	eminently hydraulic lime.
1.00–1.20	Portland cement.
1.15–1.60 *	natural cements.
1.60–1.90	puzzolans (slag cements).

The cementation index affords a better basis for the classification of hydraulic cementing materials than does the hydraulic index, but it cannot be the sole basis of classification, because it is rigidly fixed by an assumption as to the essential constitution of all this class of materials. If it could be granted that the essential constituents of hydraulic cements are tricalcium silicate and dicalcium aluminate (with the corresponding compounds formed by the replacement of lime by magnesia, or alumina by iron oxide), the fact must still be recognized that the extent to which the lime combines with silica, alumina, etc., during manufacture to form these compounds is dependent upon a number of variable factors, among which the temperature of burning is the most influential. (As a matter of fact we now know that the characteristic aluminate is the tricalcic not the dicalcic aluminate.)

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* A few natural cements show indices below 1.15 or above 1.60.

It must be concluded that the value of the cementation index as a basis of classification of hydraulic cements is rather limited. It has a very distinct value, however, as a basis of determination of the proper proportions of the raw materials used in making artificial cements, such as Portland cement and slag cements. It is now commonly used for this purpose by the majority of the cement chemists, and doubtless will continue in favor until the time when a more general understanding of the constitution of cements justifies a change in manufacturing practice.

In view of the present unsatisfactory state of common knowledge of cement chemistry the classification of hydraulic cementing materials herein utilized will be one which is based upon physical properties and method of manufacture, rather than upon chemical characteristics. The following classification is a modification of one proposed by Mathews and Grasty.*

(1) *Common Lime.* Lime made by burning relatively pure limestone at a very low temperature, the product being one which slakes when mixed with water and which possesses no hydraulic properties.

(2) *Hydraulic Limes.* Limes made by burning slightly argillaceous limestones at a low temperature, the product being one which will slake slowly but which at the same time possesses feebly hydraulic properties.

(3) *Natural Cements.* Cements made by burning distinctly argillaceous limestones at a comparatively high temperature, the product being one which will not slake, but which when ground possesses hydraulic properties.

(4) *Portland Cement.* Cement made by burning an artificial mixture of argillaceous and calcareous materials at the temperature of incipient vitrification, the product being one which will not slake but which when ground possesses marked hydraulic properties.

(5) *Puzzolan or Slag Cements.* Cements made by incorporating slaked lime with granulated blast furnace slag or a natural puzzolanic material such as volcanic ash without subsequent burning, the product being one which will not slake, but which when ground possesses hydraulic properties.

HYDRAULIC LIMES

General

39. Definition and Classification. "The hydraulic limes include all those cementing materials (made by burning silicious or argillaceous limestones) whose clinker after calcination contains so large a percentage

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* E. B. Mathews and J. S. Grasty, "The Limestones of Maryland."

of lime silicate (with or without lime aluminates and ferrites) as to give hydraulic properties to the product, but which at the same time contain normally so much free lime that the mass of clinker will slake on the addition of water." *

It will be seen that the hydraulic limes occupy an intermediate position between the common limes and the more complex cements. According to their content of clayey matter they may be classified as " feebly " or " eminently hydraulic limes," the latter including " grappier cements." Both are feebly hydraulic as compared with good natural cements or with Portland cement.

The feebly hydraulic limes, i.e., those whose cementation index lies between 0.30 and 0.70, are occasionally treated with sulphuric acid or plaster of Paris to produce a secondary product called " selenitic lime " which will be briefly mentioned hereinafter. Eminently hydraulic limes, i.e., those whose cementation index lies between 0.70 and 1.10, produce during manufacture a by-product called " grappiers," which are lumps of under-burned and over-burned material which do not slake. Finely ground grappiers constitute the cement called " grappier cement."

40. The Hydraulic Lime Industry. Uses of the Hydraulic Limes. The hydraulic lime industry is one of considerable importance in Europe, especially at Tiel, France, where the largest and best-known plants are located, and in England, where considerable quantities of feebly hydraulic limes are produced. In the United States no effort has ever been made to introduce hydraulic lime manufacture, not because of any lack of the proper raw materials, but because of the abundance of materials suitable for the manufacture of natural cements and Portland cement, with which the relatively feebly hydraulic and weak hydraulic limes and grappier cements cannot compete as a structural material.

A number of hydraulic limes and grappier cements possess, however, a certain value for architectural purposes by reason of their light color, and the further fact that they are " non-staining cements," i.e., they contain so slight an amount of iron and soluble salts that they do not stain masonry. A considerable amount of hydraulic lime and grappier cement is therefore annually imported and used for purposes of architectural decoration.

MANUFACTURE OF HYDRAULIC LIMES

41. Hydraulic Limestones. The ideal hydraulic limestone rock should have such a composition that, after all the silica has combined with lime during calcination, sufficient free lime remains to disintegrate

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* Eckel, " Cements, Limes and Plasters," p. 172.

the kiln product by the expansive force set up when it is slaked. In practice, however, not all the silica will combine with lime, and in order to avoid an excess of uncombined lime it is necessary that the content of the rock be lower than is theoretically desirable. The inevitable replacement of a part of the silica by alumina and iron oxide is also a consideration which causes departure in practice from theory, because these latter constituents act as fluxes, facilitating the formation of lime silicate, and also themselves combine with lime to form aluminates and ferrites of lime.

The limestones actually used in the manufacture of eminently hydraulic limes usually contain from 40 to 50 per cent of lime and magnesia (the latter rarely exceeding 1.0 per cent), 7 to 17 per cent of silica, and usually not to exceed 1.0 per cent of alumina and iron oxide. (Occasionally the latter constituents amount to as much as 10.0 per cent.)

Feebly hydraulic limes are usually made from limestones containing from 45 to 50 per cent of lime and magnesia, 4 to 10 per cent of silica and 4 to 8 per cent of alumina and iron oxide.

The difference in composition of limestones suitable for the manufacture of eminently hydraulic limes, and those which produce feebly hydraulic limes, is evidently a matter of higher silicon content and lower alumina and iron oxide content in the limestones which yield the product of greatest hydraulicity. The percentage of total carbonates is about 70 to 80 per cent for eminently hydraulic limestones, and 80 to 90 per cent for feebly hydraulic limestones.

42. Calcination. The burning of hydraulic limes is accomplished in continuous kilns like common lime kilns. The operations involved in the process of calcination are, in fact, practically identical for common lime and for hydraulic lime except that the temperature required is somewhat higher in the latter case. (Not less than 1000° C.) The proper temperature of calcination is directly dependent upon the composition of the rock and therefore bears a direct relation to the value of the cementation index. If the cementation index is less than 0.70, as is the case with the feebly hydraulic limes, it is practically impossible to avoid an excess of free lime, and all limes of this class do contain a large amount of uncombined lime. As the value of the index becomes more than 0.70 there is less and less danger of an excess of free lime in the product until with values approaching 1.00 the difficulty is to obtain a product with sufficient free lime to slake properly and produce a finely disintegrated product.

43. Slaking and Subsequent Treatment. The theory of slaking of hydraulic lime differs from the slaking of common quicklime in no respect except that in the former case the quicklime, which will slake, is intimately associated in lumps with lime silicate, unburned or at least under-burned limestone, and some aluminate and ferrites, none of which can be slaked. The expansion of the quicklime in slaking, however, breaks up the entire mass into a fine powder which will consist principally of lime silicate together with one-fourth to one-third as much hydrated lime.

The slaking of hydraulic lime was at one time commonly done by the purchaser upon the work. It is now, however, practically the universal practice to slake the lime at the place of manufacture. The lump lime as drawn from the kiln is spread out in thin layers and sprinkled lightly with water. It is then shoveled into heaps or bins where it is allowed to remain for about ten days till the slaking is completed by the aid of the steam generated. In order that the product may be a fine, dry powder, the slaking must be done carefully and with just the right amount of water.

A certain proportion of the kiln product either does not contain sufficient lime or is not sufficiently burned to be slaked upon the addition of water, and consequently remains as hard lumps called " grappiers." The slaked material is therefore passed over screens of about 50 meshes per linear inch, which reject all of the larger particles. This rejected material (grappiers), is valuable or not according to whether it consists principally of lumps of lime silicate on the one hand, or worthless raw or unburned limestone on the other hand. As a rule all of the grappiers are finely ground under millstones (no selection of good and bad being practicable), and a certain proportion is added to the lime, thereby increasing its hydraulicity in proportion to the amount of lime silicate present. The ground grappiers are also separately marketed as a special cement known as " grappier cement."

It is practicable to market the ground grappiers as grappier cement only when the proportion of lime silicate is high, producing therefore a cement which approaches natural cement in its properties, with the added advantage of being a " non-staining," very light-colored cement.

Selenitic limes are made from English feebly hydraulic limes by the addition of not more than 5 per cent of ground plaster of Paris to calcined hydraulic lime. The mixture is subsequently finely ground. Selenitic lime is sometimes called " Scott's cement " after the inventor and patentee of the process.

PROPERTIES OF HYDRAULIC LIMES

44. Composition. The composition of various hydraulic limes is indicated by the following table:

ANALYSES OF HYDRAULIC LIMES

	SiO_2.	$Al_2O_3+Fe_2O_3$.	$CaO+MgO$.	Num. Ave.
		Feebly Hydraulic Limes.[1]		
Ave.	10.99	8.84	79.55	5
Max.	16.05	12.77	84.55	
Min.	7.60	5.14	72.98	
		Eminently Hydraulic Limes.[2]		
Ave.	24.40	10.90	50.03	43
Max.	34.58	16.97	65.29	
Min.	14.60	3.15	41.93	
Usual limits	22–26	9–13	47–57	
		Grappier Cement.[3]		
Ave.	25.68	6.11	59.13	6
Max.	27.50	11.40	63.84	
Min.	22.15	2.90	53.66	

[1] Summary of 5 analyses quoted by Eckel, "Cements, Limes, and Plasters."

[2] Summary of 43 analyses quoted by Tetmajer, "Methode und Resulte der Prüfung Hydraulischen Bindemittel," pp. 140–143. (The author has omitted analyses Nos. 30, 39, 40, and 41, which are abnormal, from the summary.)

[3] Summary of six analyses quoted by Candlot, "Cementes et Chaux Hydrauliques," p. 178.

45. Physical Properties. The physical properties of hydraulic limes are indicated by the following data from the works of Tetmajer and Candlot previously cited.

TETMAJER'S TESTS OF EMINENTLY HYDRAULIC LIMES[1]

(AVERAGE OF 22 LIMES)

	Specific Gravity.	Weight, Lbs. per Cu. Ft.		Ignition Loss.	Setting Time.		Fineness, per cent Retained on Sieve of Meshes per Lin. In.	
		Loose.	Well Shaken.	Per cent.	Initial. Hrs. Min.	Final. Hrs. Min.	76	180
Ave.	2.766	49.0	71.5	12.14	3 : 02	54 : 18	13.39	
Max.	2.97	55.2	86.4	19.14	11 : 00	144 : 00	21.8	
Min.	2.59	39.7	52.0	5.63	0 : 03	7 : 00	4.0	

CANDLOT'S TESTS OF GRAPPIER CEMENTS.[2]

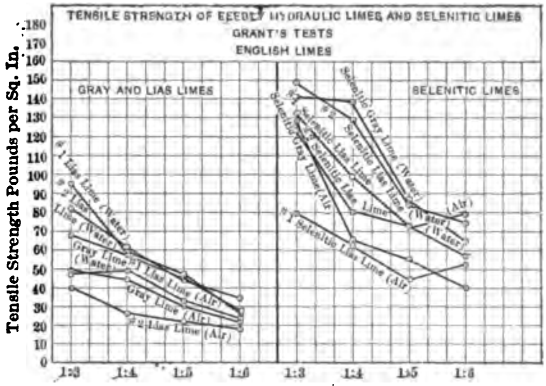
(AVERAGE OF 7 CEMENTS)

Ave.	......	53.7	......	......	......	12 : 24	4.14	17.57
Max.	......	57.4	......	......	......	15 : 00	16.00	36.0
Min.	......	47.5	......	......	......	10 : 00	0.0	9.5

[1] Tetmajer, pp. 376–378.

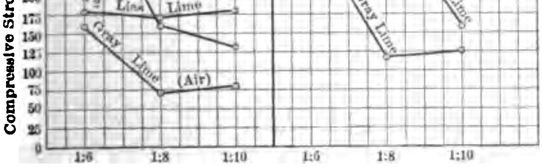
[2] Candlot, p. 179.

46. Tensile and Compressive Strength. The tensile and compressive strength of feebly hydraulic lime mortars are indicated by the curves of Figs. 26 and 27 which have been plotted from tests made by John Grant in England about 1880.* The gray lime mentioned is a typical English feebly hydraulic lime; the lias limes are somewhat more silicious limes, and therefore less feebly hydraulic; and the selenitic limes noted are ones prepared from the same gray and lias limes. Each of the curves of Fig. 26 represents the average of five tests of tensile specimens whose minimum cross-section was made $1\frac{1}{2}$ inches square. The curves of Fig. 27 represent the average of 10 compressive tests of 6-inch mortar cubes, the aggregate used being a sand and gravel mixture.



Proportions of Mixture.
FIG. 26.

These tests were made long before methods of testing had been standardized, even for cement, and consequently the values shown are of little value except that they show that tensile specimens stored in water are about 60 per cent stronger than similar specimens stored in air, and that the addition of lime sulphate to the calcined limes, thus producing selentic. limes, practically doubles the strength. (All of the tests of Mr. Grant were made at the age of one year.)



Proportions of Mixture.
FIG. 27.

At the first glance the strength values shown by these curves appear

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* Minutes of Proceedings of Civil Engineers, Vol. 62, p. 165.

excessively low. The mortar mixtures, especially those used in the compressive tests, are, however, extremely lean ones, and if the proportions were expressed by weight instead of by volume, as is the present practice, the mixtures would appear even leaner to one accustomed to the use of the term 1 : 3, 1 : 4, etc., meaning proportions by weight.

The strength of eminently hydraulic limes in neat and mortar mixtures is indicated by the curves of Fig. 28, which are based upon Tetmajer's tests of the limes whose physical properties have been tabulated in Art. 45 above. The author has summarized Tetmajer's results and expressed the values in English units in the following table:

TETMAJER'S TESTS OF EMINENTLY HYDRAULIC LIMES

	1 : 3						Neat.					
	7 days.	28 days.	84 days.	210 days.	1 year.	2 years.	7 days.	28 days.	84 days.	210 days.	1 year.	2 years.
Tension, Air Storage												
Ave.......	100.7	184.5	211.9	400.2	306.5	287.0	92.4	184.4	307.5	433.8	541.9	553.3
Max......	236.1	385.5	367.0	526.3	614.4	344.2	123.7	250.3	406.8	493.5	779.4	
Min......	43.7	82.5	76.8	230.4	155.0	183.5	75.4	91.0	79.7	293.0	143.7	
No. tests..	(8)	(8)	(8)	(3)	(8)	(4)	(6)	(6)	(6)	(5)	(6)	(1)
Tension, Water Storage												
Ave.......	56.8	108.5	210.9	304.3	316.2	325.6	66.0	129.8	235.6	308.6	352.2	460.8
Max......	95.3	174.9	342.8	465.1	463.7	409.6	108.1	179.2	345.6	421.0	439.5	
Min......	32.7	46.9	102.4	166.4	213.3	268.8	29.9	82.5	153.6	253.6	300.1	
No. tests..	(16)	(22)	(22)	(17)	(22)	(12)	(8)	(8)	(8)	(7)	(8)	(1)
Compression, Air Storage												
Ave.......	511.0	900.3	1184.7	2409.1	1834.0	1709.6	455.1	1026.2	1884.0	2769.7	2918.3	3213.2
Max......	981.7	1779.0	2201.5	2903.3	3552.9	2200.5	776.5	1415.2	2580.0	3590.0	4147.4	
Min......	196.2	398.3	632.9	1763.4	1016.9	1112.2	190.6	791.2	1103.6	1947.2	1514.7	
No. tests..	(8)	(8)	(8)	(3)	(8)	(4)	(6)	(6)	(6)	(5)	(6)	(1)
Compression, Water Storage												
Ave.......	342.5	676.9	1189.9	1806.7	1924.9	2116.9	330.5	720.4	1543.1	2579.6	3026.3	4083.4
Max......	709.7	1109.4	2511.5	3648.5	3625.6	2988.4	634.4	995.6	2508.9	3285.4	3642.6	
Min......	123.7	300.1	587.4	933.0	1110.7	1318.4	146.5	448.0	816.4	1479.3	19995.6	
No. tests .	(19)	(20)	(22)	(17)	(22)	(12)	(7)	(8)	(8)	(7)	(8)	(1)

The curves indicate that the strength of hydraulic lime and hydraulic lime mortars is about one-half in the case of tensile strength, and about one-fourth in case of compressive strength, that of average Portland cement. The rate of gain in strength is very slow, however, and the maximum strength is not attained in a period short of one year. A comparison of the neat strength with the strength of 1 : 3 mortar indicates that the sand-carrying capacity is excellent, the mortar strength averaging from two-thirds to three-fourths the neat strength. Specimens stored in air appear to gain in strength somewhat more rapidly at first, as a rule, than do specimens stored in water after three days in air. The subsequent gain in strength of the water-stored specimens is usually slightly more rapid, however, so that at the end of one year the strength of the two sets of specimens is nearly equal.

One interesting feature of these tests is the apparent fact that hydraulic limes are only about five times as strong in compression as they are in tension. With Portland and natural cements this ratio is at least 8, which indicates that the inferiority of hydraulic limes to Portland or even natural cements is much more pronounced than would be indicated by a comparison of the tensile strengths of similar mixtures. (Relative tensile strengths are unfortunately, and quite without justification, often made the sole basis of comparison of cements.) The eminently hydraulic limes are, however, immensely superior in strength to the feebly hydraulic limes and to ordinary non-hydraulic limes.

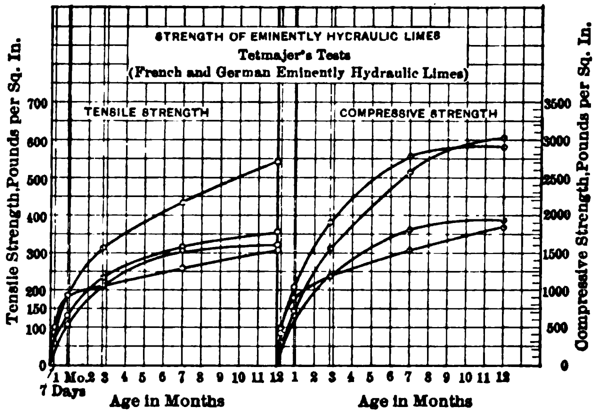

FIG. 28.

47. Hydraulic Limes in Construction. Hydraulic limes were at one time considerably used by engineers for various structural purposes. This was, however, principally before the advent of the greatly superior natural cements, and now the latter product is being almost entirely replaced as an hydraulic cementing material by Portland cement.

Hydraulic limes are not suitable for use on subaqueous construction, in spite of their designation; they are too slow setting to render their use on general construction work convenient and practical, and their comparative weakness makes competition with natural and Portland cement absolutely impossible. Their only present value, as has been previously stated, is that of an architectural decorative material rather than a material for engineering construction.

CHAPTER V

PUZZOLAN CEMENTS.* SLAG CEMENTS

PUZZOLAN CEMENTS

48. General. The oldest known hydraulic mortars were undoubtedly made by the incorporation of a volcanic tufa with slaked lime and sand. Thus were produced the cements extensively used by the Romans and other ancient peoples in the construction of many engineering structures, a few of which remain to-day in a remarkable state of preservation.

The activity of the volcanic material depends upon the presence of weakly acid silico-aluminates which combine more or less readily with lime hydrate at atmospheric temperatures. If the silica were more strongly acid its ability to combine with the base would be increased and the product would be one of superior hydraulic properties. This principle explains the fact that lightly burned clay will react with lime to form an hydraulic cement, and a weakly hydraulic mortar has even been produced by simply mixing brick dust with hydrated lime.†

49. Definition of Puzzolans and Puzzolan Cement. The natural or artificial materials which contain a sufficiently large percentage of available silica to combine with lime hydrate and form a cement possessing hydraulic properties are known as " puzzolans " or " puzzuolanas."

Puzzolan cements include all that class of hydraulic cementing materials which are made by the incorporation of natural or artificial puzzolans with hydrated lime without subsequent calcination.

Puzzolan cements have never attained any great commercial importance in the United States. A small amount of this cement has been produced for a great many years, however, and a considerably larger amount

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* The term " puzzolan," which is commonly applied to this class of cements by American authorities, is a corruption of the name " puzzuolana " which refers to the class of volcanic material first utilized as a hydraulic cementing material at the town of Puzzuoli, near Naples. Continental writers call these cements " puzzuolana " cements.

† Bleininger, Geological Survey of Ohio, Fourth Series, Bull. 3, p. 25.

is produced in Europe. Nowhere does the importance of the industry compare at all with that of the Portland, or even the natural cement industry.

The true puzzolan cement, often called " slag cement," made by incorporating blast-furnace slag with hydrated lime without subsequent burning, must not be confused with the Portland cement, which is made by finely pulverizing the clinker derived by the calcination of an intimate mixture of the same materials. This class of Portland cement is one of considerable commercial importance and will be later discussed under the head of Portland cement.

50. Natural Puzzolanic Materials. All natural puzzolanic materials of any commercial importance as cement materials are of the same general character and have a like geological origin. All are direct products of volcanic action and the commercial puzzolanic materials are invariably derived from deposits of more or less agglomerated volcanic ash.

The natural puzzolanic materials and the principal artificial puzzolanic material, granulated blast-furnace slag, have their origin in practically the same processes. In both cases a more or less finely divided siliceous material is derived by the sudden cooling and ejection into air or immersion in water of a fused silico-aluminous material.[*]

The only natural puzzolanic material of commercial importance as cement materials are " puzzuolana," " trass," " santorin " and " tuff" or " tufa." The latter material, as will be later noted, has been used in making only one brand of cement, and in that case it is not used in conjunction with lime, but is finely ground and mixed with an equal amount of ordinary Portland cement and the resulting blend subsequently finely pulverized to produce a " tufa-Portland " cement, which is neither a true puzzolan nor a true Portland.

Puzzuolana was first obtained in Italy by early Greek colonists who opened workings at the town Puzzuoli in the vicinity of Naples. The material was subsequently exploited by the Romans and is still an article of Italian commerce. Puzzuolana is also derived from several localities in southeastern France and from the Azores. The material derived from the two latter sources is now held in higher esteem than the original Italian puzzuolana. Trass is an earthy or consolidated pumiceous dust mixed with fragments of pumice and other minerals. It is derived from the valley of the Rhine in Prussia.

Santorin is an unconsolidated volcanic ash derived from the island of Santorin or Thera in the southeastern part of the Grecian Archipelago.

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[*] Eckel, " Cements, Limes and Mortars," p. 633.

The following average analyses of natural puzzolanic materials are quoted by Eckel: *

AVERAGE ANALYSES OF NATURAL PUZZOLANIC MATERIALS

	Puzzuolana, Italy.	Puzzuolana; France.	Puzzuolana, Azores.	Trass, Germany.	Santorin.	Average of All Puzzolans.
Number of analyses..	9	7	3	11	1	31
SiO_2	50.98	41.91	57.78	53.78	66.37	51.08
Al_2O_3	15.55	16.16	15.15	17.38	13.72	16.30
Fe_2O_3	14.41	19.30	10.37	6.89	4.31	11.13
CaO	7.39	6.93	2.84	3.89	2.98	5.46
MgO	1.96	1.37	1.63	1.17	1.29	1.50
K_2O, Na_2O	6.63	5.15	4.52	6.82	7.05	6.21
H_2O	5.09	7.89	7.61	9.22	4.06	7.64

If these analyses be compared with the analyses of hydraulic limes given on page 66, the necessity for the addition of lime to form an hydraulic cement will be at once apparent. The puzzolans contain twice as high percentages of silica, alumina, and iron oxide as do the eminently hydraulic limes, and yet contain only about one-seventh as much lime and magnesia.

51. Manufacture of Puzzolan Cements from Natural Materials. The preparation of puzzolan cements is a very simple mechanical process involving nothing more than the screening, mixing, and grinding of the two constituents employed.

Most deposits of natural puzzolans are subject to great variation in the quality of the material, therefore necessitating careful selection or sorting of the quarry product to exclude inferior material. Screening of the puzzolan is usually necessary in order to exclude undesirable adulterants and, in the case of the Italian puzzuolana, roasting at moderate temperatures is occasionally resorted to in order to increase its hydraulic properties.

Puzzolanic rock is, in European practice, not usually mixed with hydrated lime at the place of manufacture, but is simply pulverized and marketed as a material to be incorporated with hydrated lime paste and sand where used in construction work. The proportions of the mixtures used in mortars are not fixed, but the proportion of lime usually amounts to from one-third to one-half the proportion of puzzolan, and the puzzolan cement thus formed may be combined with any proportion of sand up to about three times the proportion of cement.

A less commonly followed practice, but one which should result in the production of a more homogeneous and satisfactory material, consists

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* Eckel, "Cements, Limes and Plasters," p. 638.

in the grinding at the place of manufacture of a mixture of the puzzolanic rock and dry hydrated lime. Cement made by this method is, of course, ready for immediate use, and is simply mixed with water and sand on the work, just as is the case with hydrated lime or hydraulic lime.

52. Properties and Uses of Natural Puzzolan Cements. Puzzolan cements made from natural materials hold so unimportant a place among structural materials that little study of their physical characteristics has been made, and no data obtained in recent investigations of their properties have been given publicity.

The tensile and compressive strengths of three puzzolan cements tested by Dr. Boehme * are presented by the curves of Fig. 29. All specimens were composed of one part by weight of puzzolan cement to three parts by weight of sand. Similar tests were made on specimens hardened in air and other specimens hardened in water, the strength being determined for each at seven days and at twenty-eight days. In every case the specimens stored in water were found to be stronger than the corresponding air-stored specimens.

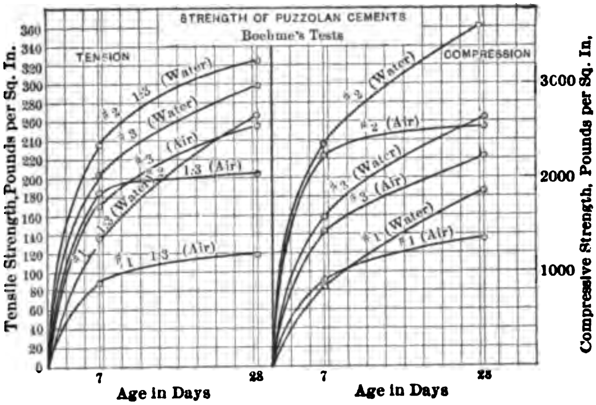

FIG. 29.

If these curves be compared with those of Fig. 28, which represent the strengths of eminently hydraulic limes, only those curves which represent strengths of 1 : 3 mortars being compared, it appears that puzzolans hardened in air are about equal in tensile strength to eminently hydraulic limes similarly hardened, but that puzzolans hardened in water are about three times as strong in tension as the hydraulic limes hardened under the same conditions. In compressive strength the puzzolans appear to be from two to five times as strong as hydraulic limes.

Average 1 : 3 Portland cement mortars excel these puzzolans by at least 30 per cent in tensile strength, but show little or no advantage over the puzzolans in compressive strength at these early periods.

Puzzolan cements produced from natural materials were in the days of the Roman Empire the only known hydraulic cementing materials, and the excellence of some of this cement is attested by the many sur-

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* Mittheilungen aus den K. technischen Versuchsanstalten zu Berlin, 1890, p. 256.

viving examples of early Roman construction in concrete. As an article of present day commerce, however, its importance is almost negligible, and in the United States the small amount of puzzolan cement used in construction is almost entirely derived from the treatment of blast furnace slag and therefore comes under the head of slag cement.

SLAG CEMENTS

53. Definition. Slag cement may be defined to be an intimate mechanical mixture of granulated blast-furnace slag of suitable chemical composition, with hydrated lime, the materials having been finely pulverized before, during, or after mixing.

No calcining of the mixture is practiced, and the product is not to be confused with the true Portland cement which is produced by the calcination and subsequent pulverization of a properly proportioned mixture of blast-furnace slag and raw limestone.

54. Blast-furnace Slag. Required Composition and Physical Conditions. Blast-furnace slags, such as are suitable for use in slag cements, are fusible lime silicates derived as waste products from the operation of blast furnaces in smelting iron from its ores. The slag is formed for the most part by the combination in the furnace of the earthy part of the ore, i.e., the " gangue," with lime from limestone which is charged with the ore as a flux. Slags are produced in many metallurgical processes other than the reduction of iron ores. Only the latter process, however, is capable of producing the very basic slag required for cement manufacture.

The required composition of the slag according to American practice is within the following approximate limits: CaO, 48 to 50 per cent; SiO_2, 32 to 35 per cent; Al_2O_3, 12 to 16 per cent, MgO, Fe_2O_3, S, etc., 2 to 5 per cent. (The latter constituents are merely incidental, not required.) In the practice of many European plants the proportion of alumina is somewhat above this range and the proportion of silica somewhat lower.

Slag, as derived from the blast furnace and allowed to cool slowly, is a very dense and hard material, and has, moreover, such a chemical constitution that even when pulverized it does not combine energetically with water, nor exhibit more than very feebly hydraulic properties. If the molten slag is cooled very rapidly, however, by the use of cold water, it becomes broken up into small porous particles which can be economically handled by the pulverizing machinery.

Two important chemical effects are also attained by the process of granulating the slag; the slag is rendered more hydraulic, thus providing a stronger cement, and the content of undesirable sulphides always encountered in slags is reduced by the formation and passing off of hydrogen disulphide.

The remarkable effect of granulating the slag upon the hydraulic properties of cements made therefrom is illustrated by Figs. 30 and 31, which are based upon the studies of M. Prost.* Fig. 30 brings out the fact that the tensile strength at one year is more than tripled by granulation of the slag, while the compressive strength, as shown by Fig. 31, is increased from five to seven-fold by granulation. At ages under one year these ratios are still larger.

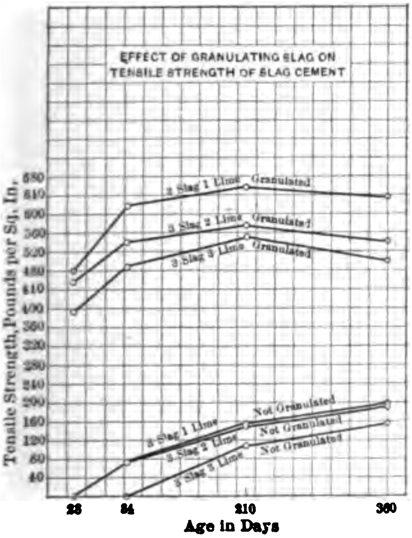

FIG. 30.

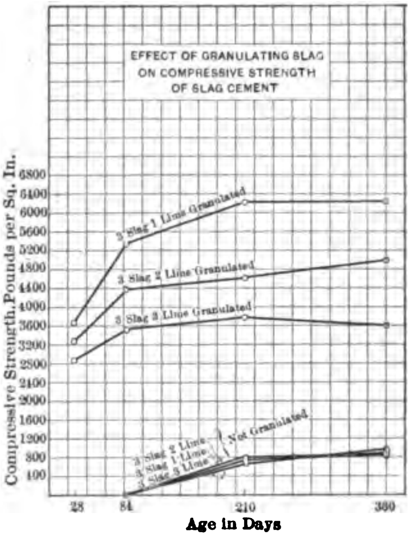

FIG. 31.

55. Manufacture of Slag Cements. The process of manufacture of slag comments involves the following operations: granulation of the slag, drying the slag sand, preparation of the hydrated lime, proportioning the mixture, mixing and grinding.

The granulation of the slag may be accomplished by a jet of high-pressure steam which the stream of slag encounters as it issues from the furnace. Air jets have also been similarly used, but both of these methods have been generally replaced by an arrangement whereby the stream of slag from the furnace falls into a trough containing a rapidly flowing stream of cold water. This method is a very satisfactory one in that it produces a slag-sand which is quite porous and friable and which is in excellent condition from the point of view of chemical composition.

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* Prost, M. A., Annales des Mines, 8th series, Vol. 16, p. 158.

It is charged with much moisture, however, and must therefore be dried before being mixed with the hydrated lime.

The slag as it comes from the bins into which it has been discharged by the granulating device, carries from 15 to 45 per cent of water. The removal of this water is accomplished through the agency of heat in either a rotary cylinder similar to those used in drying cement rock (see Fig. 41*a*), or in a vertical shaft dryer, into which the material is introduced at the top and dried by ascending hot furnace gases as it traverses a series of inclined baffle plates toward the base. Rotary dryers are used exclusively in the United States.

The hydrated lime used in slag cement in American practice is a very pure high-calcium lime, the magnesia content being in fact only a few tenths of 1 per cent. In a few instances, in European practice particularly, a semi-hydraulic lime is used whose content of silica, alumina, and iron oxide combined may amount to as much as 6 or 8 per cent. The quicklime is commonly hydrated at the cement mill.

The proportioning of the mixture of slag and lime is usually done according to some established standard found by experiment at each plant to produce the most satisfactory cement with the materials in hand. The standard proportions of slag and lime vary therefore at different plants from as low as 25 pounds of lime, to as high as 45 pounds of lime, for 100 pounds of slag sand. The proportioning might of course be done by application of the cementation index as suggested by Eckel, the slag and the lime having first been analyzed. Eckel states that the values of the cementation index found on examination to represent the proportions used at various plants ranges from 1.6 to 1.9, 1.7 being a very satisfactory value. (The method of calculating the mixture by use of the cementation index is explained in detail in Art. 86.)

Practice as to method of grinding and mixing the slag and lime is subject to great variation. The best practice probably consists in grinding the slag sand in a ball mill or other type of grinder suitable for the intermediate reduction of cement materials, adding the hydrated lime, and accomplishing the mixing and final pulverization of the mixture simultaneously in a tube mill or other type of cement-finishing mill.

Slag cements are normally more slowly setting than Portland cements and on this account are often treated with some class of puzzolanic material which will hasten the setting. Materials so used are burned clay, high-alumina slags, certain active forms of silica, and in the patented "Whiting" process, caustic soda, sodium chloride or potash. The amount of such materials added as an accelerator does not usually exceed about 3 per cent by weight, and unless the material is to qualify under the usual specifications for Portland cement no accelerator should be necessary. Any addition to the cement made for the purpose of regulating the set must of course be made prior to final pulverization.

56. Properties and Uses of Slag Cements. The usual range of composition of American slag cements is indicated by the following summary of analyses of 5 different cements quoted by Eckel.

SiO_2.	$Al_2O_3+Fe_2O_3+FeO$	CaO.	MgO.	S.	CO_2+H_2O.
27.2–31.0	11.1–14.2	50.3–51.8	1.4–3.4	0.15–1.42	2.6–5.3

The specific gravity of slag cements usually ranges between 2.7 and 2.85, which fact affords a means of distinguishing slag cements from natural cements, which rarely fall below 2.9, and Portland cements, which must under the standard specifications be not less than 3.1.

The fineness of grinding practiced in making slag cements is about equal to that commonly attained in grinding Portland cements. From 1 to 8 per cent is retained on a sieve of 100 meshes per lineal inch, and from 10 to 25 per cent on a 200-mesh sieve.

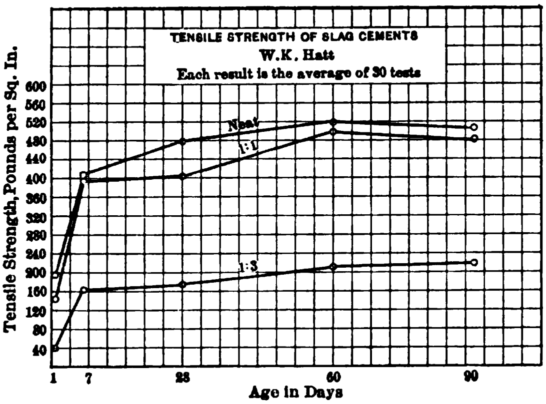

FIG. 32.

As above noted, the setting of slag cements is somewhat slower than that of Portland cements. This is more particularly true of European cements, however, as most American slag cements have had their set artificially regulated by additions made prior to grinding, and they are in consequence able to meet the specifications for setting time of Portland cement, i.e., initial set occurs in not less than thirty minutes, and final set in from one to ten hours.

The tensile strength of American slag cements is shown by the curves of Fig. 32, which are based upon tests made by Professor W. K. Hatt at Purdue University.* It will be noted that the tensile strength of 1 : 1 mortar is nearly equal to that of the neat cement, whereas the 1 : 3 mortar develops only about 40 per cent of the neat strength. These curves

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* Engineering Record, Vol. 43, pp. 196–197.

average the results obtained in tests of four brands of slag cement. Crushed quartz sand between the 20 and the 30-mesh sieves was used.

The results of compressive tests of two of these same cements, also reported by Professor Hatt, are shown by the curves of Fig. 33. Comparative curves are given for two series of specimens, one of which was allowed to harden in air, the other in water. From a comparison of these curves it appears that slag cement mortars harden and gain in strength most rapidly when stored in water. More extensive investigation of this point revealed the fact that the tensile strength of neat slag cement specimens hardened in air averages about 77 per cent of the strength of similar specimens hardened in water. For 1 : 1 mortars this ratio averaged 78 per cent, and for 1 : 3 mortars its value was 74 per cent. Comparing compressive strengths, these ratios were found to average 81 per cent for neat specimens, 90 per cent for 1 : 1 mortar, and 96 per cent for 1 : 3 mortar.

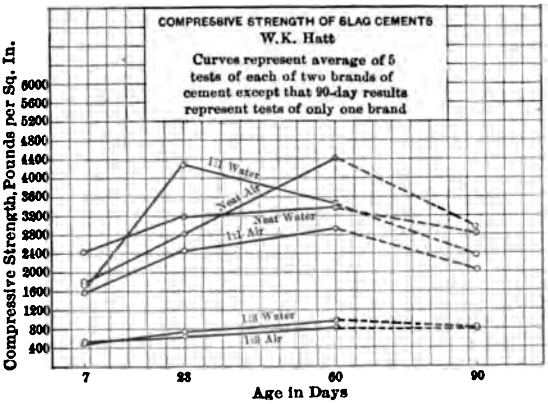


FIG. 33.

The tensile strengths of these cements and mortars are little more than half the average strengths of Portland cements and mortars, and the compressive strengths are about one-third the strength of Portland. It will be noted by comparing Figs. 32 and 33 with Figs. 30 and 31 that these American slag cements fall considerably below the strength values found by Prost using European slag cements.

The uses to which slag cement may be put are usually limited to unimportant structures or to work requiring large masses of concrete masonry where weight and bulk are more important than great strength. It is seldom used on structures above the foundations, and never used on comparatively light reinforced concrete construction. The industry is one of declining importance, as is shown by the fact that the annual production of slag cement, which reached its highest point (557,252 barrels) in 1907, had fallen to 107,313 barrels in 1913, only four plants being then in operation. For every pound of slag cement produced or used in the United States, more than 1000 pounds of Portland cement is made and used.

CHAPTER VI

NATURAL CEMENTS

GENERAL

57. Definition. Distinction between Natural and Portland Cements. Natural cements have been classified above (Art. 28) as cements which are made by burning distinctly argillaceous limestones at a relatively high temperature, the product being one which will not slake with water, but which possesses the hydraulic properties after grinding.

It now becomes necessary to define natural cements in terms of such restricted meaning that there may exist no possibility of confusing natural cements with any other class of cementitious materials.

Natural cement may be defined as the finely pulverized product resulting from the calcination of an argillaceous limestone at a temperature sufficient to drive off the carbon dioxide gas and also decompose the clay and effect the formation of aluminates, ferrites and silicates.

The definition given by the American Society for Testing Materials differs from the above definition in that it prescribes that the calcination shall be effected "at a temperature only sufficient to drive off the carbonic-acid gas." The latter definition means the exclusion of practically every natural cement made in this country, for only a very few natural cements are or can be successfully burned at a temperature not exceeding that necessary to drive off the carbonic-acid gas.

The distinctions between natural and Portland cements may be summarized as follows:

	Natural Cements.	Portland Cement.
Raw material...........	Natural argillo-calcareous rock	Artificial argillo-calcareous mixture
Calcination Temperature.	Low	Relatively high
Chemical Composition...	Variable, not under control	Controllable within narrow limits
Color.................	Usually yellow to brown	Usually blue-gray
Specific gravity.........	2.7 to 3.1	3.1 to 3.2
Rate of setting..........	Normally rapid	Relatively slow
Strength..............	Low	Relatively high

58. Natural Cement as a Structural Material. Natural cement is used structurally as the cementing ingredient of concretes and, in combination with sand, as a mortar for laying brick and stone masonry, and as an outside wall plaster. A certain amount is also used as an addition to lime mortars for the purpose of increasing the strength thereof. In all of these applications it comes into direct competition with Portland cement, with respect to which it often suffers by comparison. In consequence of a growing distrust of natural cement and the improvement in the quality of Portland cement produced during the last fifteen years, accompanied by the decrease in cost of the latter, natural cement has found itself gradually being crowded from the field of construction materials. Because of the declining importance of the natural cement industry and the greatly reduced extent to which its use is permitted on masonry construction work, far less detailed consideration will herein be given to its manufacture and properties than will be accorded Portland cement.

MANUFACTURE OF NATURAL CEMENTS

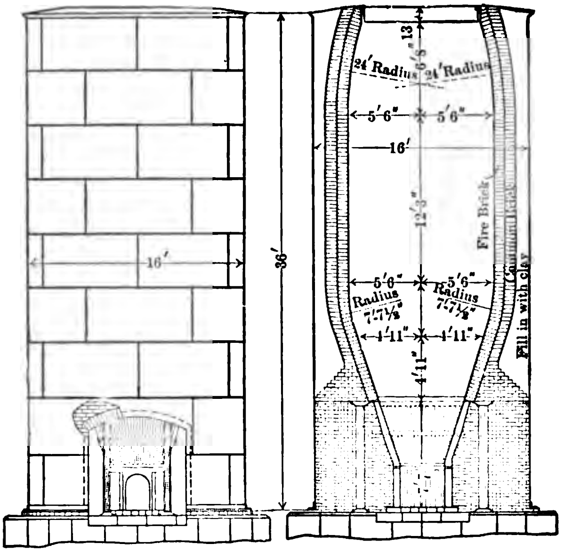
59. Natural Cement Rocks. Natural cements are invariably made by the calcination of a natural clayey limestone carrying from 13 to 35 per cent of clayey material, 10 to 20 per cent of the clayey material being silica, and the balance alumina and iron oxide. The hydraulic properties of the cement are entirely due to the presence of this clayey material. The calcium carbonate of the limestone may be and very commonly is replaced to a considerable degree by magnesium carbonate, resulting in the replacement of lime by magnesia to a corresponding degree in the manufactured product. This latter fact is without great significance since, so far as the hydraulic properties of the natural cement are concerned, lime and magnesia may be regarded as almost exactly interchangeable.

Argillaceous limestones of the composition required for the manufacture of natural cement are widely distributed, there being in fact hardly a state in the United States where such rock is not found. In spite of this wide geographical distribution, however, there are only comparative few districts where the natural cement industry has ever become commercially successful. This fact is due to the necessity for certain commercial advantages dependent upon the character and location of the quarries. Among these requisites may be mentioned a rock of at least fairly uniform composition, a favorable location of the rock beds for cheap extraction of the cement rock, cheap fuel, a good local market for the product, and good transportation facilities.

60. Theory of Calcination. From the composition of the raw material given above it will be seen that the rock as it is charged into the kiln consists essentially of lime and magnesium carbonate with a more or less definite percentage of clayey matter. The chemical changes that take place during calcination may be briefly mentioned as follows:

Water mechanically held by the rock is driven off at temperatures little above 100° C.; at a temperature of about 750° to 800° C. magnesium carbonate is dissociated, the carbon dioxide being driven off, leaving the magnesia; at a temperature of 900° C. or less the lime carbonate is similarly dissociated, leaving lime; at a temperature of 900° to 1000° C. the clay is decomposed and the formation of aluminates and ferrites of lime and magnesia is effected; lastly, if the temperature is carried to 1100° to 1300° C., as it usually is, silicates of lime and magnesia are formed. If the rock could be perfectly burned the loss in burning (the difference in weight of raw material and marketable product) would correspond exactly to the percentage of carbon dioxide+water in the rock. Practically, the losses will exceed this amount by about 25 per cent on account of under-burning and over-burning of a portion of the material.

61. Practice of Calcination. *The Kiln.* The type of kiln almost exclusively used in the United States' natural cement industry is of the continuous vertical mixed feed type, the rock and fuel being either mixed or charged in alternate layers. For present purposes a description of one type of kiln of modern design will be given as typical of the kilns used in present American practice.



FRONT ELEVATION SECTION

FIG. 34.—Campbell Kiln for Natural Cement.

The Campbell kiln (Fig. 34) consists of an inner cylindrical kiln of masonry, lined with firebrick and enclosed by a sheet-steel cylinder separated from the masonry by a thick layer of clay. The interior diameter of the kiln is 11 feet from a point about 9 feet above the pot to a point about 8 feet below the top. The kiln gradually narrows below this zone to a diameter of about 6 feet 7 inches at the top of the pot, and above this zone to a diameter of about 9 feet. The height of the kiln above the top of the pot is about 28 feet. The pot is an open grating of iron in the form of an inverted cone about 3 feet 6 inches in diameter at the bottom where the calcined material is withdrawn. The capacity of such a kiln is from 125 to 150 barrels (265 pounds) per day. Other types of kiln in common use in America differ from the Campbell kiln in only one essential detail—the replacement of the iron kiln-pot by a masonry pot. The Campbell is somewhat more economical to build and more convenient in operation.

The Fuel. The fuel used in natural-cement burning is bituminous coal. The fuel consumption varies greatly, because differences in composition of the rock cause variation in the required calcination temperature. The average fuel consumption is about 12 pounds of coal per 100 pounds of cement produced, the variation being from a minimum of about 6.5 pounds to a maximum of 18 pounds.

62. The Clinker. The output of a natural-cement kiln includes three classes of material, hard-burned clinker, soft porous moderately burned material, and practically unburned material. The existence of these three classes of calcined material is due to three facts: variation in the composition of the rock charged, variation in the management of the kiln, and variation in the degree of heat to which the material in the kiln has been subjected. The recognition of the presence of these three classes of material is necessary, because with some rocks the best cement is derived from the soft moderately burned material, and in many cases the best cement is a mixture of both materials. Unburned material is valueless.

63. Free Lime. With cement rock high in lime and magnesia the possible range of temperature for proper calcination is shortened, with consequent greater possibility of dangerously high percentages of free lime. The presence of this free lime may be neutralized by some method of slaking the lime. This is commonly done by sprinkling or steaming the unground clinker, and in some cases by simply aërating the clinker. This expedient decreases grinding costs, since the slaking of the lime will to some extent disintegrate the clinker.

64. Grinding and Packing. In the early days of the manufacture of natural cement in America the universal practice was roughly to crush the clinker in some simple form of crusher, followed by fine grinding between millstones. This equipment has now been largely superseded by grinders such as the Sturtevant " rock-emery " mill (Fig. 35), the Cummings grinder (Fig. 36), and various types of grinders and pulverizers commonly used in Portland cement manufacture, such as the gyratory crusher, the Griffin mill, the Huntington mill, the kominuter, the ball mill, the tube mill, the Fuller-Lehigh mill, etc.

In the Sturtevant "rock-emery" mill the ordinary mill stones are replaced by "rock-emery" stones, which consist of a cylindrical shell of steel enclosing the abrasive. The center of this stone is simply a disc of buhrstone surrounded by a zone set with slabs of "rock-emery" cemented by metal poured while molten. Radial strips of buhrstone are set to continue the furrows of the central buhrstone to the rim of the wheel.

The Cummings grinder crushes material between two vertical chilled-iron discs, one of whichis stationary, while the other is revolved at high speed. The faces of both discs are cut into a series of bands and furrows to facilitate the rapid distegration of the materials.

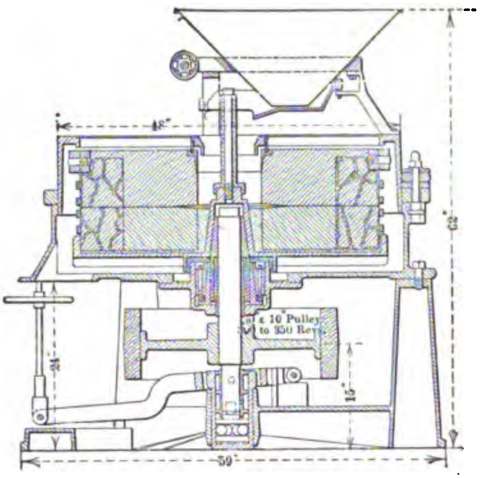


Fig. 35.—Sturtevant Rock-emery Mill.

The construction and operation of the mills commonly used in the Portland cement industry will be illustrated and discussed in Chapter VII, and therefore need not be further mentioned here.

The packing of natural cement differs in no respect from the packing of Portland cement, to be discussed later. The standard of the Americal Society for Testing Materials prescribes packing in bags of 94 pounds net weight, three bags to the barrel. Practice varies in respect to packing weights, however; some companies have adopted 300 pounds net weight for their standard barrel, some 280 pounds, and still others 265 pounds.

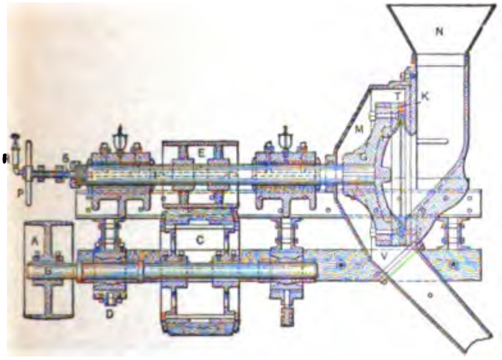


Fig. 36.—Cummings Grinder.

65. Manufacturing Costs. Manufacturing costs in the natural cement industry will vary greatly, depending upon the nature and availability of raw material, the cost of fuel, the mechanical equipment of the plant, and the cost of labor. In general the manufacturing costs will vary between about 20 cents per barrel under most favorable circumstances, and 50 cents per barrel under very unfavorable conditions.

PROPERTIES AND USES OF NATURAL CEMENTS

66. Chemical Composition. Constitution. The average composition of various natural cements is indicated by the following summary, which shows the range in composition found upon averaging a number of analyses of each of six well-known American natural cements. (Each figure represents an average for one brand, and individual samples of each brand will be found to be outside the average limits stated.*)

SiO_2.	Al_2O_3.	Fe_2O_3.	CaO.	MgO.
22.3–29.0%	5.2–8.8% .	1.4–3.2%	31.0–57.6%	1.4–21.5%

In addition to these principal constituents all natural cements contain varying small amounts of alkalies, sulphur trioxide, carbon dioxide, and water.

It will be apparent from the above summary that the composition of natural cements is extremely variable, and since wide variations in composition are accompanied by great differences in mechanical properties, this circumstances is in no small degree responsible for the widespread distrust of natural cements.

The typical constitution of natural cements does not differ materially from that of Portland cements, and discussion of the matter will therefore be taken up in Chapter VII.

67. Specific Gravity. The specific gravity of natural cements is as above noted slightly below that of Portland cements. The standard specifications of the Am. Soc. for Testing Materials make no stipulation concerning specific gravity. Eckel quotes many tests of the more prominent brands which show a range of from 2.70 to 3.17 with an average of 2.96.

68. Time of Setting. Natural cements normally are quick setting as compared with Portland cement. The standard specifications prescribe that the initial set shall take place in not less than ten minutes, and hard set in not less than thirty minutes or more than three hours.

The time of setting of natural cements is materially affected by aëra-

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* These data are abstracted from a large number of analyses of individual cements of six different brands, quoted by Eckel, " Cements, Limes and Plasters," pp. 204–213.

tion. Sabin * found with ten natural cements of widely varying rates of setting, nineteen days aëration retarded the initial set on the average about 43 per cent, the cements naturally least quickly setting being retarded the most. The final set after the same aëration was found to have been retarded on the average 3.6 per cent, the more quickly setting cements being retarded the most.

The addition of gypsum or plaster of Paris also has a very marked effect in retarding the set of natural cements, the degree of retardation with a given percentage of gypsum being largely dependent upon the chemical composition of the particular cement used. Sabin experimented with two brands of natural cement to which varying percentages of gypsum were added. Both brands showed a maximum retardation in initial set (180 per cent and 225 per cent respectively) when 2 per cent gypsum had been added, while the maximum retardation in final set in each case (24 per cent and 275 per cent respectively) was experienced when 3 per cent of gypsum was employed.

69. Fineness. The important bearing of fineness of grinding upon the strength and other properties of cement was formerly overlooked for the most part by manufacturers of natural cement. In recent years, however, they have been compelled to look about for means of improving their product in order to be able to compete at all with Portland cements. With the awakening has come the more general adoption of modern types of grinding machinery and a greatly improved degree of fineness of grinding. Formerly, the grinding was rarely carried further than was necessary to pass 95 per cent of the material through a 30-mesh sieve, which was, indeed, all that most specifications required. Now the general practice is to meet and even exceed the requirements of the standard specifications of the Am. Soc. for Testing Materials which permit a maximum residue of 30 per cent on the 200-mesh sieve and 10 per cent on the 100-mesh sieve.

70. Tensile Strength. In tensile strength natural cements vary quite as much as they do in other physical properties. This variation is found not only in comparing cements from different localities, but even in comparing samples taken at different times from the output of any one locality. The only general statement that may be made concerning their strength is that natural cements rarely show more than half the tensile strength of Portland cement of the same age. This is true not only of neat cement, but also of mortars of all proportions. Tests made by Sabin † upon ten representative brands of natural cement have been averaged and the curves of Fig. 37 plotted therefrom. One notable

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* Sabin, "Report, Chief of Engineers," 1895, p. 2937.

† Sabin, loc. cit., p. 2937.

feature of these tests is the fact that practically no retrogression is encountered even after two years, and many other tests of natural cements establish the fact that natural cements do not normally show retrogression. This is of great significance in view of the fact that the majority of Portland cements show retrogression before the six-month period has expired, and practically all Portlands retrogress between the six-months' and the eight-months' periods.

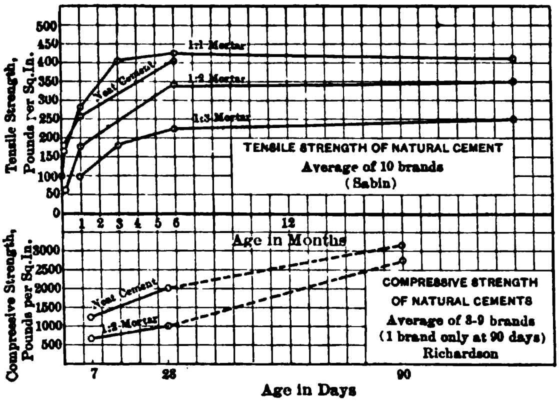

FIG. 37.

The standard specifications of the Am. Soc. for Testing Materials fix the following minimum requirements for tensile strength:

	Neat Cement, Lbs. per Sq. In.	1 : 3 Standard Mortar. Lbs. per Sq. In.
24 hrs. in moist air	75	
24 hrs. in moist air, 6 days in water	150	50
24 hrs. in most air, 27 days in water	250	125

It is further stipulated that the cement shall show no retrogression in strength within the periods specified.

71. Compressive Strength. The above remarks concerning the variability of tensile strength of natural cements apply equally well to compressive strength. The average compressive strengths of a number of natural cements tested by Clifford Richardson are shown by the curves of Fig. 37.* In general it may be stated that the compressive strength of natural cement, neat or mortars, rarely exceeds one-third that of Portland cement in similar mixtures.

The ratio of compressive strength to tensile strength for cements and mortars is in the neighborhood of 5 to 6 for neat cement and 3.5 to 5 for the mortars. These values are scarcely more than one-half the ratios found to obtain with Portland cement.†

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* Brickbuilder, Vol. 6, p. 253.

† See Report, Chief of Engineers, U. S. A., 1896, p. 2872.

The standard specifications make no mention of compressive strength.

72. Modulus of Elasticity. The ratio of stress to strain for cement and mortars cannot be considered exactly constant even for small loads. The age of the mortar when tested also has a considerable effect upon the results obtained, the progressive change in the value of the stress-strain ratio with increasing loads being considerably less marked as the age increases. The following tabulation giving a summary of tests made upon 12-inch cubes at the Watertown Arsenal * shows the progressive change in the modulus with increased range of load:

MODULUS OF ELASTICITY, LBS. PER SQ. IN.

Range of Load.	100-600	100-1000	100-2000
1 : 1 mortar........	2,147,000	1,709,000	1,081,000
1 : 2 mortar........	1,324,000	1,266,000	1,042,000
1 : 3 mortar........	955,000	804,000	

(In using the term " modulus of elasticity " referring to the behavior of an imperfectly elastic material under load, we mean simply the quotient obtained by dividing any stress increment by the strain increment which accompanies it. This is admittedly an incorrect use of the term, but is nevertheless a common practice.)

73. Where Natural Cement May be Used. When economy is effected thereby, natural cement may be substituted for Portland cement in mortars and concrete for dry heavy foundations where the stresses encountered will never be high and will not be imposed for several months after the placing of the concrete, for backing or filling in massive masonry in dry situations where weight and mass are more es sential than strength, for laying brick and stone masonry subjected only to light loads and not exposed, for pavement foundations, for sidewalks, etc. It should not be used in exposed situations, should not be placed under water, it is unsuited for use in marine construction, and should not be used in building construction above the foundation.

74. Production and Value of Natural Cement. Statistics of the natural cement industry in the United States are presented in the table below which has been taken from " Mineral Resources of the United States." As a matter of convenience, and to afford direct comparisons the statistics of the Portland cement industry and the puzzolan cement industry are also presented at this point.

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* Tests of Metals, 1902.

PRODUCTION OF CEMENT IN THE UNITED STATES

Year.	Natural.		Portland.		Puzzolan.	
	Barrels 265 Lbs.	Ave Price per Bbl.	Barrels 380 Lbs.	Ave. Price per Bbl.	Barrels 330 Lbs.	Ave Price per Bbl.
1870–1880	22,000,000					
1880	2,030,000	....	42,000?	3.00?		
1885	4,000,000	0.80	150,000	1.95		
1890	7,082,204	0.69	335,500	2.09		
1895	7,741,077	....	990,324	1.60		
1896	7,970,450	....	1,543,023	1.57	12,265	
1897	8,311,688	....	2,677,775	1.61	48,329	
1898	8,418,924	0.47	3,692,284	1.62	150,895	1.50
1899	9,868,179	0.52	5,652,266	1.43	335,000	1.47
1900	8,383,519	0.45	8,482,020	1.09	446,609	1.27
1901	7,084,823	0.43	12,711,225	0.99	272,689	0.73
1902	8,044,305	0.50	17,230,644	1.21	478,555	0.81
1903	7,030,271	0.50	22,342,973	1.24	525,896	1.03
1904	4,866,331	0.50	26,505,881	0.88	303,045	0.75
1905	4,473,049	0.54	35,246,812	0.94	382,447	0.71
1906	4,055,797	0.60	46,463,424	1.13	481,224	0.86
1907	2,887,700	0.51	48,785,390	1.11	557,252	0.79
1908	1,686,862	0.49	51,072,612	0.85	151,451	0.63
1909	1,537,638	0.42	64,991,431	0.81	160,646	0.62
1910	1,139,239	0.42	76,549,951	0.89	95,951	0.66
1911	926.091	0.41	78,528,637	0.84	93,230	0.83
1912	821,231	0.45	82,438,096	0.81	91,864	0.84
1913	744,658	0.46	92,097,131	1.01	107,313	0.91

(Prices stated are f.o.b. at the works and do not include cost of barrels or bags.)

75. Status of the Industry. Reference to the foregoing table will show that natural cement reached its maximum output in 1899, 9,868,179 barrels. Beginning with 1904, the industry has shown marked and continuous decline in production each year, and its production for 1913, 744,658 barrels, is the lowest on record since 1870. At the same time the value of the product has depreciated even more rapidly than the quantity produced, the average net price being 46 cents per barrel in 1913, as compared with 52 cents in 1899, and 60 cents in 1906.

One of the primary reasons for the decline of the natural cement industry is suggested by a comparison of the production of natural cement during the last twenty years with the production of Portland cement for the same period. It will be seen that the period of decline for the natural cement industry is practically coincident with a period of phenomenal growth in the Portland cement industry, this growth being accompanied by a drop in average price of Portland cement from $2.09 in 1890 to $0.81 in 1912 and 1.01 in 1913.

Taking into account the fact that the average natural cement barrel contains 265 pounds, as compared with 380 pounds for Portland cement, it appears that the relative cost of natural and Portland cement is less in favor of the former from the standpoint of the consumer than would at first appear, the cost of natural being 75 per cent of the cost of the Portland pound for pound. The relative cost of natural and Portland cement mortars and concretes is also dependent upon the relative proportion of cement necessary in each case. Since the average natural cement possesses not more than half the strength of the Portland cement in neat or mortar mixtures, and an even lower ratio for concretes, it will be evident that the mixture required will be much richer to attain a given strength if natural cement be used. In general, the cost of the additional amount of natural cement required will, therefore, more than offset the advantage due to difference in unit price. One consideration favoring the selection of natural cement in preference to Portland cement for certain classes or mortar should be mentioned in this connection. A mortar of 1 : 2 mix natural cement may be required, for instance, in the construction of certain classes of brick or even stone masonry where mixture of 1 : 4 Portland cement will suffice. The advantage in cost will perhaps be slight either way, the richer natural cement mortar will, however, be preferable to the Portland cement mortar with its heavy burden of sand, because the former will work much more easily under the trowel and thereby enable the mason to increase materially the speed with which the work can be done.

In the above discussion we have neglected to take account of the cost of transportation of the cement, always a large factor in total cost. It is very possible that this factor may entirely change the relative cost of the two classes of cement in a given district. Frequently it has happened that Portland cement has required long transportation to a market in the vicinity of natural cement plants. Under these circumstances competition is impossible on the class of work to which natural cement is adapted. This consideration accounts also for the fact that for many years the market for each natural cement has been a local one.

CHAPTER VII

PORTLAND CEMENT

GENERAL

76. Historical. The use of a cementitious material composed of calcareous and argillaceous substances so far antedates authentic history that we have no knowledge when or by whom it was discovered or first employed. It was used by the ancient Egyptians in the construction of portions of the pyramids, which have endured for more than 4000 years. The Romans constructed many aqueducts, walls, and buildings of cement concrete, some of which are still existent, though they are in some instances known to have been built as early as the third century before the Christian Era. The pools of King Solomon near Jerusalem were built of concrete and still furnish water for the city. The Colosseum of Rome has concrete foundations; the Pantheon of Rome has a dome 142 feet in diameter built mainly of concrete and still in perfect condition after 1900 years. In many other old-world countries there exist many examples of the ancient use of concrete. The lookout towers of Ireland, for instance, supposed to have been built by the Druids more than 1000 years ago, are made of hydraulic cement concrete. In the new world concrete was used by the Peruvians in the days of Incas, and in North America the Mound-Builders, a race believed to have been existent 11,000 years ago, made utensils of artificial stone.

Through the period of stagnation known in history as the Middle Ages the making of cement and concrete appears to have become a lost art. Not until the eighteenth century was cement again made or concrete used. To an English engineer, John Smeaton, who was commissioned to build the Eddystone lighthouse, must be credited the rediscovery of a process of making hydraulic cement. Finding lime mortar unsatisfactory for his purposes, Smeaton began in 1756 a series of experiments in the course of which he discovered that the calcination of a clayey limestone yielded a product superior in every way to ordinary lime and possessing the property of setting under water. Smeaton used, however, only that part of the limestone which yielded a product which would slake with the addition of water. His discovery was therefore an hydraulic lime. Forty years later, in 1796, Joseph Parker of Kent County, England, took out a patent for the process of manufacture of a cement which he called "Roman cement," and which he made by burning and subsequently grinding argillo-calcareous nodules called "septaria," the composition of which resembles many of the natural cement rocks of the present day. Parker obtained the nodules principally from the shores of the Isle of Sheppy, where they were washed up after a storm. This cement, the precurser of modern natural cements, came rapidly into favor in England.

In 1824, Joseph Aspdin, a brick mason of Leeds, England, was granted a patent on a method of manufacture of a cement for which he proposed the name "Portland cement," because of a real or fancied resemblance of the concrete made therefrom to the natural oölitic limestone so extensively quarried for building purposes at Portland, England. Aspdin proposed to make his cement from the dust of roads repaired with limestone, or from limestone itself combined with clay, by burning the mixture and subsequently grinding the product. Aspdin is usually given the credit for the invention of Portland cement, though it is doubtful whether he carried his investigations any further than his predecessors had done. The specifications in his patent failed to state either the relative proportions of clayey and calcareous material necessary, or the required degree of calcination of the mixture.

In the United States the cement industry began with the discovery in 1818 of a natural cement rock in Madison County, N. Y., by Mr. Canvass White, an engineer on the construction of the Erie canal. The natural cement made and patented by White was used in large quantities in the construction of the canal. Within a few years after the discovery of natural cement rock in Madison Co., N. Y., other deposits of cement rock were found, and the manufacture of natural cement began near Louisville, Ky., near Hancock, Md., at Utica, Ill., Akron, N. Y., at Balcony Falls, Va., at Siegfried, Pa., at Rosendale, N. Y., at Ft. Scott, Kan., at Buffalo, N. Y., at Milwaukee, Wis., and in many other places, all of which have at some time supported a natural cement industry of some importance.

The first Portland cement manufactured in the United States was made at Coplay, Pa., in 1875, by Mr. David O. Saylor, who had begun in 1872 to experiment with the making of Portland cement from the rock used by the Coplay Cement Co. (of which he was president) for the manufacture of natural cement. Saylor was at last successful in making a Portland cement comparable with the foreign Portlands by calcining at a high temperature a mixture of the argillaceous limestone rock with a comparatively pure limestone rock. During the next five years several Portland cement plants were put in operation in the United States, many of which were commercial failures. Between the years 1880 and 1890 the Portland cement industry slowly grew, but it was not until 1895, with the introduction of coal burning in the rotary kiln, that there began the phenomenally rapid growth which has since characterized the industry.

77. Definition of Portland Cement. In spite of a wide variation in the composition and character of the raw materials used in the manufacture of Portland cement the composition of the product derived therefrom varies only within quite narrow limits, and it would therefore seem a simple matter to define that product in a manner universally acceptable. Thus far, however, no definition has found wide acceptance.

By common agreement any definition must prescribe a material consisting essentially of lime, silica, and alumina, properly proportioned, burned to the point of incipient fusion, and finely pulverized. It is necessary, however, both in the interests of the consumer and the manufacturer, to restrict the application of the term to only those cements made in a fairly definite manner, from a somewhat restricted class of raw materials, the product having a composition within certain practical limits.

Some widely used definitions, notably that proposed as the American standard in the specifications for cement adopted by the American Society for Testing Materials, 1909, have been very loosely constructed. The trend, however, of national societies and associations is now clearly in the direction of a very restricted definition, a fact attributable, perhaps, to the quite general desire to prevent the application of the term " Portland cement " to cements made by burning a natural rock without previous artificial mixing or grinding, whatever the subsequent treatment, also to exclude cements made by mixing Portland cement with pulverized blast furnace slag, and those made by mixing natural cement with Portland cement.

With the above considerations in view the following definition of Portland cement is proposed. The definition is a modification of that proposed by the American Society for Testing Materials, its provisions being, however, more nearly in accord with the definition adopted as the German Standard by the Association of German Portland Cement Manufacturers, March 16, 1910.

Definition. The term " Portland cement " is applied to the finely pulverized product resulting from the calcination to incipient fusion of an intimate artificial mixture of argillaceous and calcareous materials, this product to contain not less than 1.7 parts by weight of lime to 1 part by weight of silica+alumina+ferric oxide, not more than 4 per cent of magnesia, nor more than 1.75 per cent of anhydrous sulphuric acid, and to which no addition greater than 3 per cent shall have been made subsequent to calcination.

Explanation. The high content of lime in Portland cement necessitates the intimate mixing of the raw materials in quite exact proportions obtainable only in an artificial way under chemical control. Burning to incipient fusion (sintering), insures the high density so essential to Portland cement. The provision allowing a maximum magnesia content of 4 per cent presupposes that this magnesia content be taken into account in adding the lime. An excess of magnesia causes unsoundness of cement. The allowance of a maximum sulphuric acid content of 1.75 per cent is necessary because of the unavoidable presence of sulphurous compounds in the raw material and in the fuel. In addition, sulphur compounds are necessarily introduced by the addition of gypsum or plaster of Paris to regulate the time of setting. The provision limiting the additions made subsequent to calcination to 3 per cent is designed primarily to prevent the possibility of additions made solely for the purpose of increasing the weight.

78. Portland Cement as a Structural Material. The use of Portland cement as a material of engineering construction is so universal that little need here be said concerning the class of construction work on which it may be used. As an ingredient of concretes and mortars it is by far the most important of all masonry materials used in modern engineering construction. As monolothic concrete it is used in all types of massive masonry works, such as foundations and footings, piers and abutments, dams, retaining walls, pavements and roadways, etc. When reinforced with steel it is used for framework, walls, floors, and roofs of buildings, for arch and girder bridges, for tunnels, subways, conduits, and innumerable other purposes. In combination with sand alone it is used as mortar for laying brick or stone work, and as a plaster or stucco it is applied to either exterior or interior walls upon a base of terra cotta, brick or metal lath.

In general cement holds rank as a structural material second only to steel and possibly timber. (Although an enormous amount of timber is used structurally, a comparatively small amount is used on important permanent work whose features possess any real interest from the strictly engineering point of view.)

One great difference exists, however, as to the conditions under which cement is used as compared with steel. The importance of this consideration cannot be over-emphasized. Steel is delivered upon the work as a finished material, manufactured under standardized conditions, every step in the metallurgical processes involved in its production, and the mechanical operations of its fabrication having been most carefully supervised. Upon the work the fabricated units are simply assembled, this operation also being done by well-standardized methods by workmen specially trained in doing this one class of work.

Cement, on the other hand, although now manufactured under fairly well-standardized conditions, usually with competent mill supervision, is received upon the work as one ingredient only of a structural material, concrete or mortar, which is built in place. The materials which are combined to form concrete or mortar, i.e., sand and crushed stone or gravel, are too often used without careful examination or selection, and —most important of all—the mixing and the deposition of the material in place is as a rule done by unskilled laborers, often without competent supervision.

These conditions are largely responsible for the fact that Portland cement concrete and mortar are not as reliable materials as is steel, and accounts for the fact that good practice does not permit its use on important work without the closest supervision at all times by the engineer in charge or his representative. Many a failure of concrete structures has been attributed to faulty cement, which should have been attributed to poor sand or stone, or to a foreman who considers that " anyone can mix and place concrete."

PORTLAND CEMENT MANUFACTURE

79. Raw Materials. The essential constituents of Portland cement are as above stated lime, silica, and alumina. (The place occupied by iron oxide, magnesia, etc., in the constitution of cement will for the present be neglected.) With the exception of lime these substances are found free in nature, but not, however, in a form practicable for use in cement manufacture. Lime is always used in the form of a carbonate, and silica and alumina in the form of clay, shale, or slate.

Eckel* makes the following classification of the raw materials:

Calcareous. ($CaCO_3$ over 75 %)	Argillo-calcareous. ($CaCO_3 = 40$-75 %)	Argillaceous. ($CaCO_3$ under 40 %)	
Pure limestone.	Clayey limestone.	Slate.	Hard.
Pure chalk.	Clayey chalk.	Shale.	Soft.
Pure marl.	Clayey marl.	Clay.	Unconsolidated.
Alkali waste.	Blast furnace slag.		Unconsolidated.

The combination of the materials in any two of these groups which will give a mixture of proper composition might be used as the raw mate-

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* "Cements, Limes and Plasters," p. 301.

rial for Portland cement. The only combinations, however, which have been used in this country are in order of their present importance:

(1) Argillaceous limestone (cement rock) and pure limestone.
(2) Marl and clay or shale.
(3) Limestone and shale or clay.
(4) Blast furnace slag and limestone.
(5) Chalk and clay.
(6) Alkali waste and clay.

While proper chemical composition and physical character are the primary requisites for the raw materials chosen, many other considerations assume great importance when the factors contributory to the economical manufacture of Portland cement are considered. Among these may be mentioned the availability of the deposits, the location with respect to a market and transportation facilities, and lastly the location with respect to fuel supplies.

80. Limestone. Limestones occur widely distributed throughout the country. When pure, limestone forms the mineral calcite ($CaCO_3$), and all limestones consist essentially of calcium carbonate combined with more or less impurities. The principal foreign elements commonly found are magnesia, silica, iron, alkalies, and sulphur.

Magnesia in the form of carbonate of magnesia occurs very commonly in limestone, but, since the effort is always made to keep the magnesia content as low as possible in Portland cement, a limestone containing much over 5 per cent of carbonate of magnesia will be unsuited for use.

Silica may be present either alone or in combination with alumina. When alone it may occur as flint in pebbles or beds, or less commonly, in the form of mica, hornblende, or other complex silicates. The silica does not readily combine with lime in the kiln, and more than a very small amount of silica renders a limestone unfit for use. Silica combined with alumina is a very common impurity in limestone and such limestones are of great value to the cement manufacturer. Compounds of silica and alumina readily combine with lime in the kiln and the argillaceous limestones are therefore among the most important classes of raw materials for the manufacture of Portland cement.

Iron occurs usually as either the oxide (Fe_2O_3) or sulphide (FeS_2), and less commonly as a carbonate or silicate. Except as a sulphide the iron forms a useful flux, aiding the combination of lime and silica in the kiln. As a sulphide it is injurious and to be avoided if in amounts over 2 to 3 per cent.

The alkalies, soda and potash, commonly occur in limestones in small percentages. Unless present in quantities over about 5 per cent, in which event they may be carried over into the cement with harmful results, they will be largely driven off in the kiln with no consequent effect upon the cement.

Sulphur may be present as iron pyrite or as lime sulphate. In either case its presence is extremely injurious and not over 1 to 2 per cent can be tolerated.

The approximate range of composition of limestones used in American Portland cement manufacture is indicated by the following summary:

Component.	Approximate Range. Per cent.	Usual Percentage.
$CaCO_3$	88.0–98.0	93.0–97.0
SiO_2	0.3– 8.0	0.4– 3.0
$Al_2O_3+Fe_2O_3$	0.2– 2.1	0.5– 1.3
$MgCO_3$	0.2– 4.2	1.0– 2.5

81. Argillaceous Limestone, Cement Rock. The term " cement rock " is technically applied to a limestone containing about 68 to 72 per cent of lime carbonate, 18 to 27 per cent clayey matter, and not over 5 per cent of magnesium carbonate. Such a rock is found in many districts of the country, but has been largely used for the manufacture of Portland cement only in the Lehigh district of eastern Pennsylvania and western New Jersey, a territory 4 miles wide and 50 miles long. This district at one time (1899) produced three-fourths of the Portland cement manufactured in the United States and even now (1913) produces nearly one-third of the entire output (29.5 per cent).

The cement rock is a dark gray to black, slatey limestone, softer than pure limestone and consequently more easily ground. As a rule the cement rock must be mixed with a comparatively pure limestone in small percentages. In a very few cases, however, the cement rock contains an excess of calcareous material, necessitating the admixture of shale or clay with the cement rock.

82. Marl. Marls are deposits of comparatively pure carbonate of lime found in beds of existing or extinct lakes. The manner of formation of marl beds is a matter of some dispute but, whether due to deposition of lime carbonate by purely physical and chemical agencies, or partly through the agency of certain vegetable and animal life, a deposit of lime carbonate in a soft, friable form, usually in a finely granular state, is formed. Organic matter, clay and carbonate of magnesia are the principal impurities found in marls, with sometimes small amounts of sulphur in combination with organic matter, iron, or lime. Marls usually analyze about 90 to 97 per cent $CaCO_3$ and $MgCO_3$, less than

1 per cent SiO_2, less than 1 per cent Al_2O_3 and Fe_2O_3 combined, the balance being made up of small amounts of organic matter, SO_3, etc. When used in the manufacture of Portland cement marls usually require the addition of from 15 to 20 per cent clay. The large percentage of water (often 50 to 60 per cent) usually present in the marl upon arrival at the plant is disregarded in the above statement of composition.

83. Clays, Shales and Slates. Clays, shales, and slate may in general be considered of the same ultimate composition, differing only in the degree of consolidation. All clays are formed from the debris resulting from the decay or rocks, and hence they will differ greatly in composition and physical character. Clays left where rock disintegrates are called residual clays, when transported and deposited by stream action they are sedimentary clays, and when they are deposited by glacial action they are glaciali clays. The different classes of clays differ in composition owing to differences in the manner of their deposition. Residual clays are apt to contain fragments of quartz, flint, or lime carbonate, depending upon the character of the rock disintegrated; sedimentary clays in their long water transportation usually have lost all their coarser material and so form a fine-grained homogeneous product; the glacial clays show even less homogeneity than the residual clays and are apt to contain much sand, gravel and pebbles.

Absolutely pure clay is hydrated silicate of alumina or kaolin (Al_2O_3, $2SiO_2$, $2H_2O$). Such a clay is not available for cement manufacture but it is imperative that the clay be as free as possible from gravel and sand. The proportion of silica should not be less than 55 to 65 per cent, and the combined amount of alumina and iron oxide should be between one-third and one-half the amount of silica (22 to 27 per cent). The presence of gypsum or pyrite in the clay is injurious, and magnesia and alkalies should not be present in quantities exceeding about 3 per cent.

Shales are simply clays hardened by pressure, but they have almost invariably been formed from deposits of sedimentary clay and so do not show the irregularities in composition common to most residual or glacial clays. Shales are preferable to soft clay for mixing with limestone because, on account of the similarity in physical character, segregation of the two is less likely to take place. They also carry less water and therefore require less drying. Clay, upon the other hand, is better adapted to use with marl.

The slates are clays which through heavy pressure have solidified in a markedly laminated structure and acquired the property of splitting readily into thin sheets. The slates find only a limited application in the manufacture of Portland cement and then only as a utilization of the waste from roofing slate works.

84. Alkali Waste. The precipitated calcium carbonate obtained from the manufacture of caustic soda by the Leblanc process has been used in Europe for the manufacture of Portland cement. This waste often carries high percentages of sulphur in the form of sulphides, however, and is thereby rendered unfit for use as a Portland cement material.

The waste from alkali works using the ammonia process is a very pure precipitated lime together with some lime-hydrate. The sulphur content is usually very low, making this waste a material superior to that derived by the Leblanc process. No Portland cement is made in the United States at the present time (1914) using any class of alkali waste as a raw material, and in view of the availability of better suited materials, it is unlikely that use of this waste will again be considered.

85. Blast-furnace Slag. Three classes of cement which must not be confused are made with blast-furnace slag as one of the ingredients. One is the slag or puzzolan cement made by grinding blast-furnace slag with hydrated lime without subsequent calcination; a second is a true Portland cement made by mixing limestone and slag, grinding the mixture very finely, and calcining the product as in the usual process of Portland cement manufacture; the third is the German "Iron-Portland" cement made by grinding finely together 70 per cent of true Portland cement and 30 per cent of granulated blast-furnace slag.

Blast-furnace slag is a fusible silicate formed during the smelting of iron ore by the combination of the fluxing material with the "gangue" of the ore. The slags used in cement manufacture are those of strongly basic character, the higher the lime the better. The following analysis is typical of the slags used in the manufacture of cements of the second class above given.

Silica	33.10
Iron oxide and alumina	12.60
Lime	49.98
Magnesia	2.45

There is a slight chemical or thermal advantage in the use of slag as a cement material owing to the fact that the lime is present as the oxide (CaO), instead of as the carbonate ($CaCO_3$), meaning therefore a saving of fuel in the kiln. On the other hand this advantage is partially offset by the fact that the granulation of the slag by running the molten material into water results in the absorption of from 15 to 45 per cent of water, which must subsequently be driven off, thus increasing the fuel consumption.

86. Proportioning the Raw Materials. The definition of Portland cement above given (Art. 77) declares it to be a material containing "not less than 1.7 parts by weight of lime to 1 part by weight of silica+

alumina+iron oxide, not more than 4 per cent of magnesia, nor more than 1.75 per cent of anhydrous sulphuric acid." The combining of the raw materials in such a manner as to achieve the desired ratio of calcareous to argillaceous materials is not, however, entirely a simple matter, for the reason that Portland cement after calcination is not a mixture of lime and clayey materials, but is what may be termed a " solid solution " of a number of components including silicates and aluminates of lime, but no free lime. The minimum ratio of lime to clayey material prescribed in the definition very roughly expresses the relative proportions in which the two classes of material are understood to combine, and the actual proportions of two given materials which will produce a satisfactory cement can only be determined upon the basis of a knowledge of the detailed composition of each of the component raw materials, and a further knowledge of the compounds which will be formed during calcination, i.e., the constitution of finished cement.

It is easy, of course, to analyze each of the constituent raw materials, but the constitution of cement, so far as the practice of cement chemists is concerned, is unknown. What is actually done under these circumstances is to proceed upon the basis of an assumption as to what the essential constituents of cement are, the assumption being as a rule based upon the investigations of cement constitution made by M. Le Chatelier and the Messrs. Newberry many years ago. The most recent studies of this problem tend to show that neither Le Chatelier nor the Newberrys were entirely correct in their conclusions, but experience has shown that the methods of proportioning which are based upon these conclusions will produce an excellent cement and, that being the case, there is no immediate prospect of any change being made in the practice of cement chemists, regardless of the results of more modern studies of the problem of cement constitution.*

The essential facts as to the constitution of cement obtained as the result of the studies of Messrs. Newberry have been briefly noted above (Art. 38). The essential constituents being considered to be tricalcium silicate and dicalcium aluminate, the proportion of lime to silica and alumina is expressed by the following rule, called " Newberry's Rule for Proportioning ":

$$\text{Max. lime} = 2.8(\%SiO_2) + 1.1(\%Al_2O_3).$$

Eckel's modification of this rule, taking account of the magnesia and the iron oxide, has also been stated and explained above (Art. 38), the form of Eckel's rule called the " cementation index " being:

$$\frac{2.8(\%SiO_2) + 1.1(\%Al_2O_3) + 0.7(\%Fe_2O_3)}{\%CaO + 1.4(\%MgO)} = 1.$$

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* See discussion of " Constitution of Portland Cement," in Art. 106, Chapter VII.

A value of the cementation index below 1 necessarily means an excess of lime or magnesia in the cement, i.e., free lime or magnesia is present. In the practical application of this rule factory chemists aim to attain a composition whose cementation index is slightly above 1.0, the proportion of the limestone used being reduced for the sake of safety about 10 per cent below the maximum called for by the rule.

The following example illustrates the application of the rule to the determination of the correct proportions of untried raw materials:

We assume that the raw materials are of the following composition:

	SiO_2.	Al_2O_3.	Fe_2O_3.	CaO.	MgO.	SO_3.	Water, CO_2, etc.
Clay	61.92	16.58	7.28	2.01	1.58	0.02	10.61
Limestone	1.54	0.39	1.04	54.97	0.52	0.04	41.50

(1) Clay:

$$\begin{aligned}\text{Silica}\times 2.8 &= 61.92\times 2.8 = 173.38\\ \text{Alumina}\times 1.1 &= 16.58\times 1.1 = 18.24\\ \text{Iron oxide}\times 0.7 &= 7.28\times 0.7 = 5.10\\ \hline & \ 196.72\\ \text{Lime}\times 1.0 &= 2.01\times 1.0 = 2.01\\ \text{Magnesia}\times 1.4 &= 1.58\times 1.4 = 2.21\\ \hline & \ 4.22\\ 196.72-4.22 &= 192.50\end{aligned}$$

(2) Limestone:

$$\begin{aligned}\text{Silica}\times 2.8 &= 1.54\times 2.8 = 4.31\\ \text{Alumina}\times 1.1 &= 0.39\times 1.1 = 0.43\\ \text{Iron oxide}\times 0.7 &= 1.04\times 0.7 = 0.73\\ \hline & \ 5.47\\ \text{Lime}\times 1.0 &= 54.97\times 1.0 = 54.97\\ \text{Magnesia}\times 1.4 &= 0.52\times 1.4 = 0.73\\ \hline & \ 55.70\\ 55.70-5.47 &= 50.23\end{aligned}$$

(3) Proportion required:

$192.50 \div 50.23 = 3.83$ parts of limestone to 1 part of clay by weight. Since, as above noted, ideal conditions of grinding and burning cannot be attained in practice, it is customary to reduce the theoretically correct percentage of limestone about 10 per cent for safety. Therefore $3.83-0.38=3.45$ parts of limestone to 1 part of clay to be actually used.

The application of a rule based upon complete analyses of the raw materials is not necessary once a plant is well established with fairly uniform raw materials. Usually a fixed standard total percentage of carbonate ($CaCO_3$ and $MgCO_3$) is found by experience with any given raw materials to give a satisfactory mixture, and this standard is thereafter maintained as long as the raw materials remain unchanged. Sometimes instead of a fixed lime standard, the ratio of total carbonates to total insoluble matter is similarly used.

87. Control of the Mixture During Operation of Plant. The ideal method of control consists in the analysis of both raw materials at the plant before grinding, grinding and mixing according to these analyses, analyzing the mixture as a check, and correcting the mix by the addition of the constituent required before calcination.

In practice, cheaper and quicker methods are adopted as a rule. Either the analysis of the raw material is entirely depended upon and no subsequent effort made to check and correct the mix, or the raw materials are ground and mixed in approximately correct proportions without analysis, and the ground mixture analyzed and then corrected by the addition of the material found deficient.

88. Treatment of Materials Preliminary to Calcination. The calcination of Portland cement materials must invariably be preceded by two processes which may or may not be distinct one from the other: (1) the reduction of the materials to an impalpable powder; (2) the intimate mixing of the materials in proper proportions. Often the mixing of the materials is accomplished simultaneously with the final pulverization and after the preliminary grinding.

The treatment of the raw materials before calcination follows, in general, one of two possible processes: (*a*) The dry process; (*b*) the wet process. The use of the latter process obtains only when the raw materials consist either of marl and clay or chalky limestone and clay, and constitutes an almost negligible portion of the cement industry in the United States.

89. Theory of Calcination. The principal chemical objects accomplished by calcination of Portland cement mixtures are, in the approximate order of their sequence: (1) the evaporation of water, (2) the dissociation of carbonates of lime and magnesia, (3) the expulsion of the alkalies, (4) the oxidation of ferrous to ferric oxides, and (5) the combination of lime and magnesia with silica, alumina, and ferric oxide to form the silicates, aluminates, and ferrites, which make up the constitution of Portland cement.

Incidentally, contact of the materials with the fuel ash, the kiln lining, and the kiln gases results in the addition of clayey constituents, silica, alumina, and iron oxide, thus very slightly reducing the proportion of lime and magnesia in the finished product.

Most of the moisture is driven off at temperatures only slightly exceeding 100° C. Lime carbonate is dissociated at temperatures somewhat above 900° C., and magnesium carbonate at temperatures probably between 800° C. and 900° C. The formation of silicates, aluminates, and ferrites does not take place at temperatures below about 1100° C., and for most commercial cement mixtures the attainment of a temperature of about 1550° C. has been found necessary in order to insure the combination of practically all of the lime with the clayey constituents.

The Dry Process

90. Quarrying, Crushing and Drying the Rock. Ninety-five per cent of the material used in Portland cement manufacture is obtained by quarrying (the handling of marl being excluded from consideration.) The first step in quarrying operations consists in stripping off the surface soil. Where the depth of stripping is not too great it may be done without power by scrapers. Where the stripping means the removal of a deep soil cover heavy excavators or hydraulic methods may be employed.

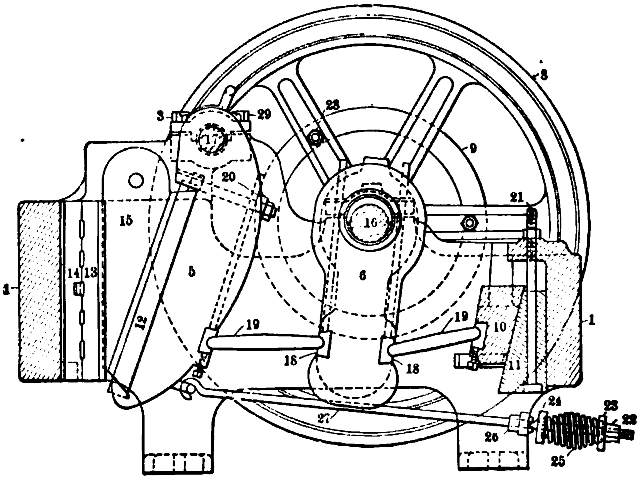


Fig. 38.—Jaw Crusher.

Quarries are usually opened on a side hill, the rock is blasted down in benches, reduced to manageable size, and removed in small cars running on movable tracks. The steam shovel is often used to load the blasted material upon the cars, and where comparatively soft material is encountered it may be depended upon to excavate the material without blasting.

Mining, the obtaining of material by underground workings in shafts or tunnels, is rarely employed in the obtaining of cement materials because of the excessive cost as compared with quarrying. Occasionally, however, a valuable stratum of cement rock, limestone, or shale may be overlaid by a thick stratum of other material, making underground working cheaper than stripping and quarrying. Mining has one advantage over open quarrying in that it is not affected by the adverse weather conditions which usually make quarrying impossible for at least one-fourth of the time.

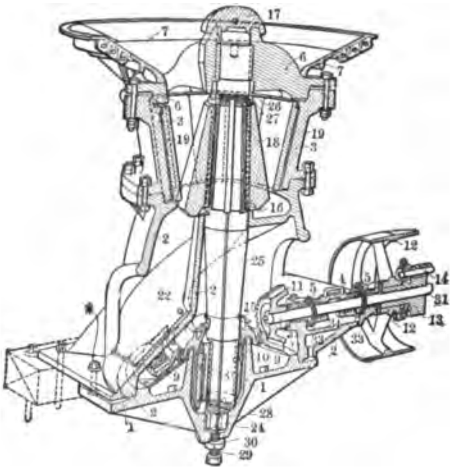


Fig. 39.—Gyratory Crusher.

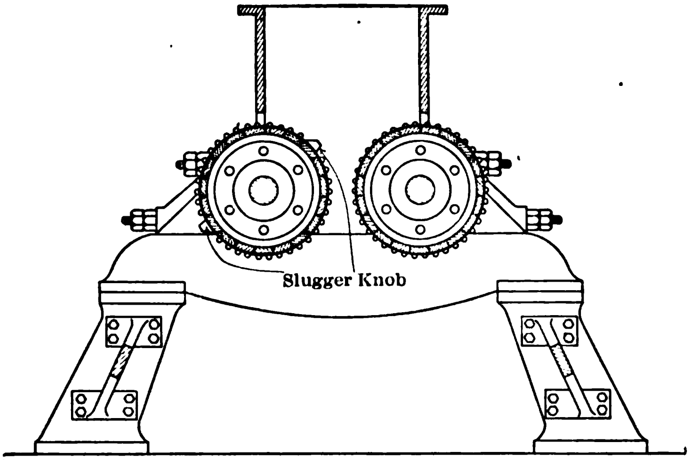


Fig. 40.—Edison Roll Crusher.

The raw materials employed in the dry process are in general in the form of more or less compact rock, either cement rock and limestone or limestone and shale. A few isolated plants where marl and clay or shale, or blast-furnace slag and limestone, are employed, constitute exceptions to the general rule.

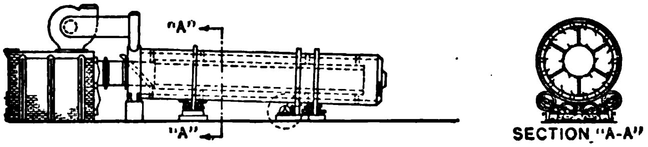


Fig. 41.—Ruggles-Coles Dryer.

Preliminary reduction is usually accomplished in a crusher of either the jaw type, Fig. 38, or, much more commonly, one of the gyratory type, Fig. 39. A roll crusher, Fig. 40, is occasionally used.

It is in many cases found economical to use more than one size of preliminary crusher, the smaller machine taking care of the smaller-sized quarry rock and the over-sized material from the larger machine.

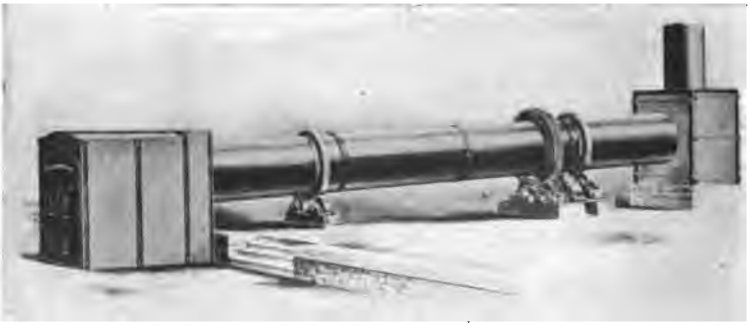


Fig. 41a.—Rotary Dryer.

The degree to which the preliminary crushing is carried is quite variable in the practice of different plants. The general practice, however, is to reduce the rock only to a size that will pass a 2- or 2½-inch ring.

The presence of moisture in the rock as it comes from the quarry very much impairs the efficiency of grinding and pulverizing machinery. It is therefore necessary to dry the rock after crushing.

The type of dryer used almost exclusively in cement mills is the rotary dryer, Figs. 41 and 41*a*. From the dryers the material is conveyed to the raw grinding mill where it is ground, mixed, and finely pulverized.

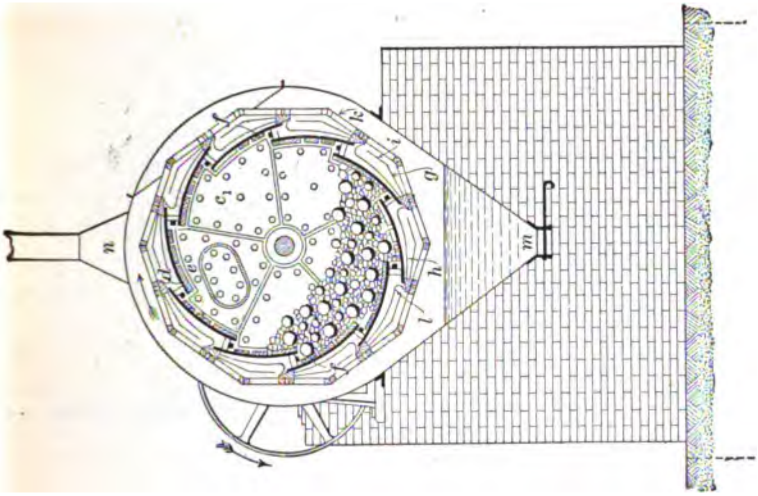


FIG. 42*b*.—Ball Mill, Transverse Section.

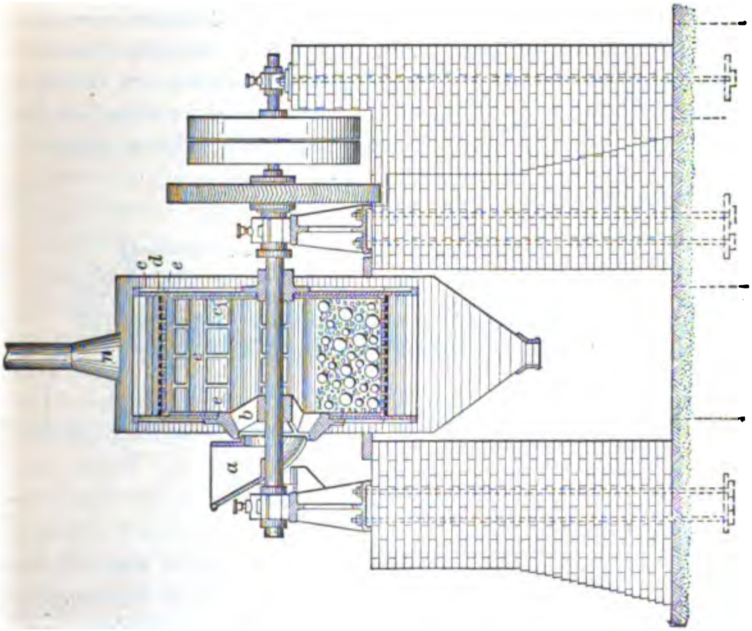


FIG. 42*a*.—Ball Mill, Section through Shaft.

91. Grinding, Mixing and Pulverizing the Raw Materials. The further reduction of raw material after drying is almost invariably carried on in two stages. In the first stage the materials, either mixed or separately, are ground to a size varying in the practice of different plants from $\frac{1}{4}$ inch down to $\frac{1}{20}$ inch or less. In the second stage the mixture of the constituent materials is pulverized to the final degree of fineness required. The choice of the type of grinding and pulverizing machinery adopted is largely dependent upon the age of the plant, the character of the raw materials, and the type of equipment originally installed.

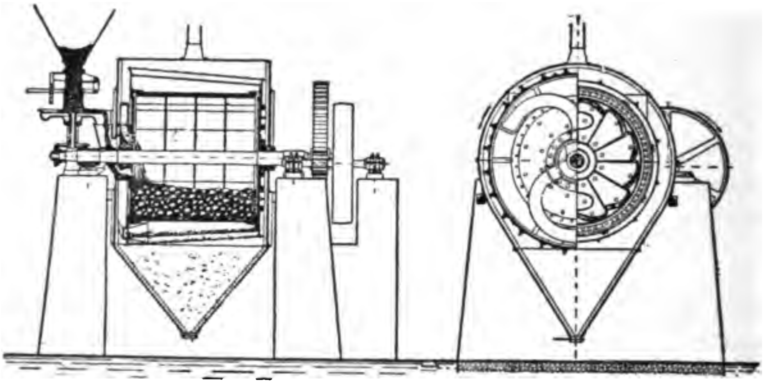


Fig. 43.—Kominuter.

Most American plants operating on the dry process use the ball mill, Fig. 42, or the kominuter, Fig. 43, for the initial grinding of the raw material, in conjunction with the tube mill, Fig. 44, or Fuller-Lehigh mill, Fig. 45, for final pulverization. The Griffin mill, Figs. 46 and 47, is to a lesser extent used for final pulverization, and the Huntington mill, Fig. 48, is similarly used in one large plant. The Williams mill and several types of rolls and disintegrators are sometimes used for raw grinding of certain classes of material, and the Raymond pulverizer is occasionally used for final pulverization.

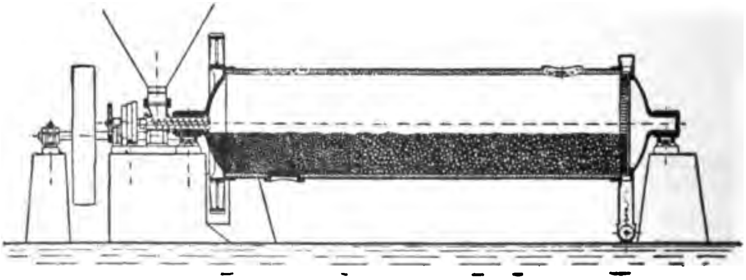


Fig. 44.—Tube Mill.

As noted above, mixing of the two classes of raw material may take place at any one of several points in the process of preparing the material for calcination. The choice depends largely upon the relative physical character of the two classes of material and the degree of uniformity in composition of the materials. Two rock ores such as limestone and shale, or limestone and cement rock, may run so nearly constant in composition that the chemist's analyses made in the quarry may be trusted, and the mixture may be proportioned by weight either just before, or immediately after crushing, without fear of segregation of the two rocks in subsequent handling. Such a combination as a limestone and a clay would give difficulty by segregation, by reason of their differing physical characters, if mixed before being reduced to a finely divided state.

Probably the point in the process where mixing is most often accomplished is immediately after initial grinding and before pulverization, an analysis of the materials having been made after grinding. In the extremely finely divided state attained in the process of pulverization a very intimate mixing without danger of segregation is accomplished.

Very often some type of mechanical weighing and proportioning machine is installed between the stages of initial and final grinding. Conveyors discharge the two materials into two hopper scales, Fig. 49, which are so devised that the contents of the two hoppers discharge simultaneously into a common hopper when the weight of material in each hopper has reached a predetermined weight dependent upon the chemist's determination of the proper proportions of the two materials.

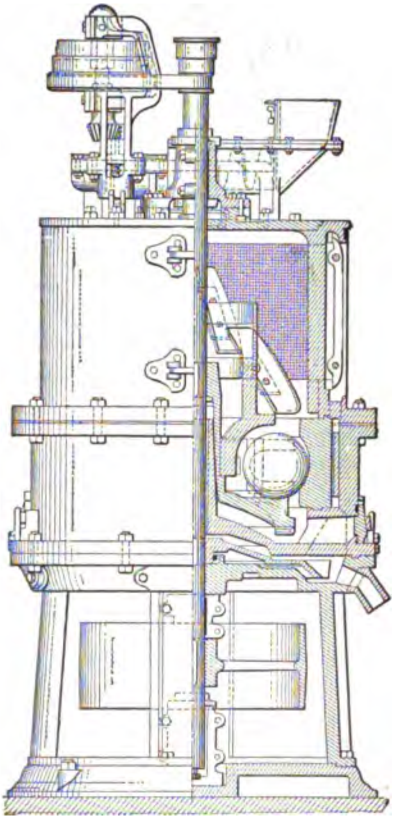


Fig. 45.—Fuller-Lehigh Mill.

Probably no other factor contributory to the production of a satisfactory cement holds so important a place as does the degree of fine-

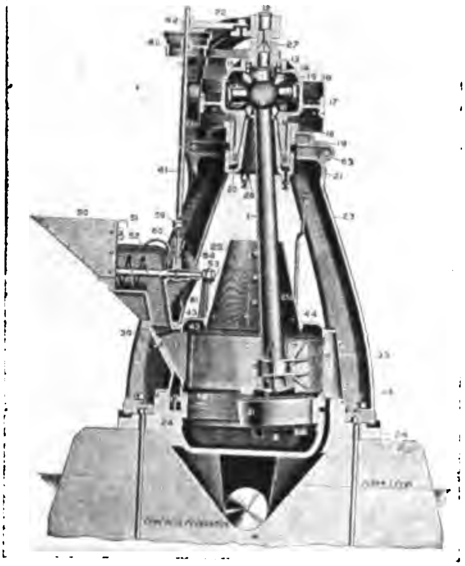


Fig. 46.—Griffin Mill.

ness attained in grinding the raw mix. The bearing of this factor is felt both in the consideration of economy of operation of the plant and in the consideration of the quality of the product.

Since the temperature of calcination is simply a sintering temperature, and not sufficient to fuse the mixture and so produce a homogenous product, diffusion between the lime and alumina and silica must take place at a temperature usually not exceeding about 1600° C. The amount of diffusion in a solid is dependent upon three factors, the temperature, the time allowed, and the amount of surface exposed or the state of subdivision of the constituent materials. Fineness of grinding will therefore lead to economy in calcination, since either the duration or the temperature of burning will be lessened by increased fineness of grinding.

On the other hand, if the temperature or duration of burning are not increased to compensate for lack of fine grinding the production of a relatively homogeneous product is impossible. There will be very imperfect diffusion between

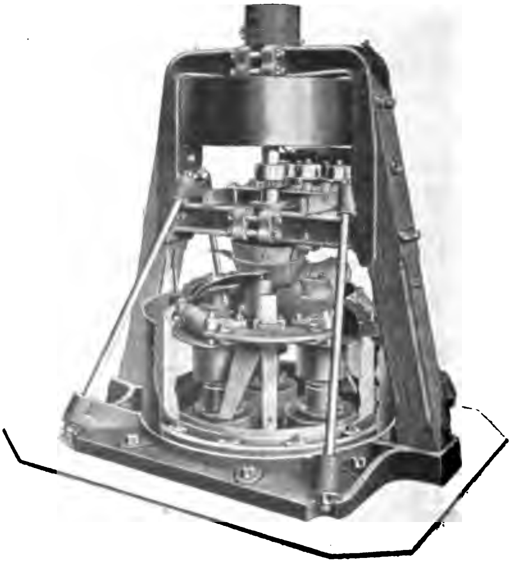


Fig. 47.—Bradley Mill.

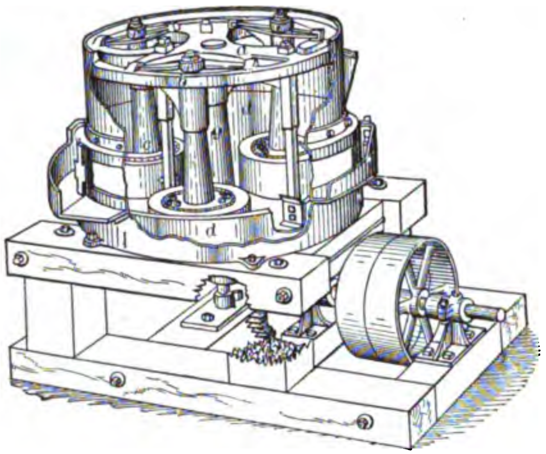


Fig. 48.—Huntington Mill.

the constituents of the mix, resulting in the production of a cement lacking volume constancy.

The actual degree of fineness attained in practice is somewhat dependent upon the character of the materials used and other local factors. The mixtures of cement rock with a relatively low proportion of limestone, for instance, require less fine grinding than do the mixtures of two pure classes of material such as a pure limestone and a clay or shale.

In general the degree of fineness required in most instances is such that not less than 95 per cent will pass the 100-mesh sieve, and as much as 98 per cent through the 100-mesh sieve is preferable.

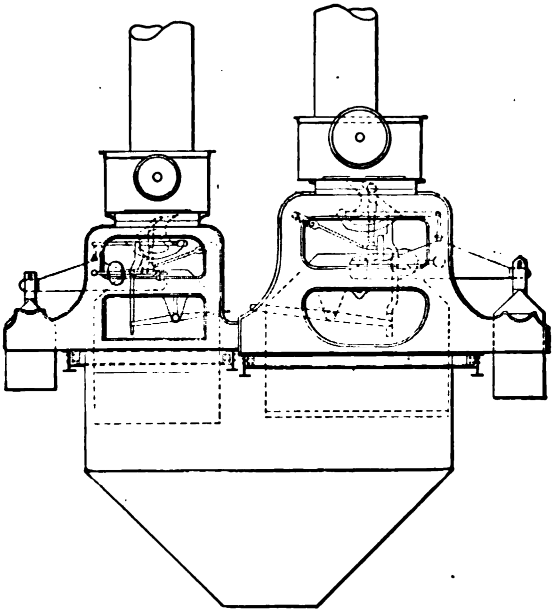


Fig. 49.—Tandem-automatic Weighing Machine.

92. Burning the Cement Mixture. For present purposes the calcination of the cement mixture may be considered to be always accomplished in the rotary type of cement kiln, Fig. 50. Differences in operating methods necessitated by the use of kilns other than the rotary type will be later noted briefly in connection with descriptions of various types of kilns.

Raw material is discharged into the kiln from the supply bins either through an inclined spout, Fig. 51, or a water-jacketed screw conveyor, Fig. 52, running through the stack flue. Usually the feeding device is belt-connected to the kiln drive so that the feeding starts and stops with the kiln. When wet slurry is burned in the kiln it is pumped in from a tank below, provision being made to make the rate of supply uniform.

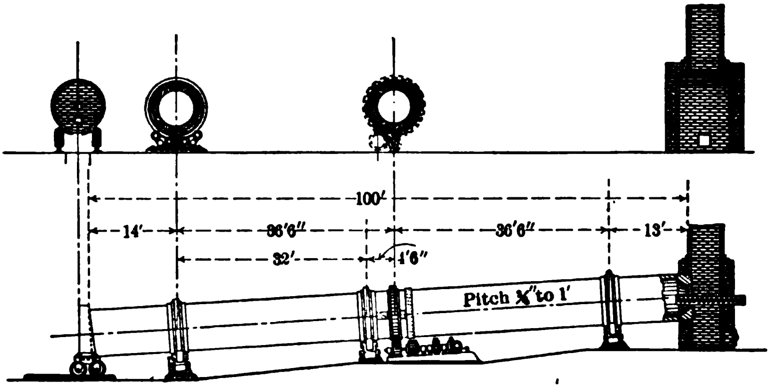


FIG. 50.—Detail Construction of a 100-foot Kiln.

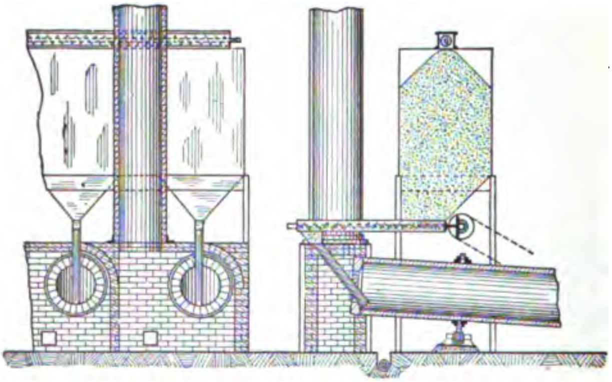


FIG. 51.—Kiln Feed by Spout.

Coal used for kiln burning is usually gas slack and should contain as little ash as possible, 25 per cent being about the maximum allowable. Coal is usually crushed in rolls or pot crushers, ball or Williams mill, dried in a rotary dryer, and pulverized in a tube mill, Fuller-Lehigh mill, Raymond mill or Griffin mill.

The pulverized coal is delivered by conveyors from the coal-grinding mill to bins located above and behind the burner end of the kiln. A screw conveyor, Fig. 53, usually carries the coal from the supply bin to a point where it falls into an air injector, where it encounters an air blast which conveys it through a pipe to a nozzle which projects a foot or more into the kiln. The air thus introduced by the blower is only about one-fourth that required for combustion, a large amount being drawn in by the natural draft of the kiln stack through the opening in the hood where the clinker escapes. The pressure of air used is sometimes very high—60 to 80 pounds per square inch—in which event only 7 to 10 per cent of the air required will be so intro-

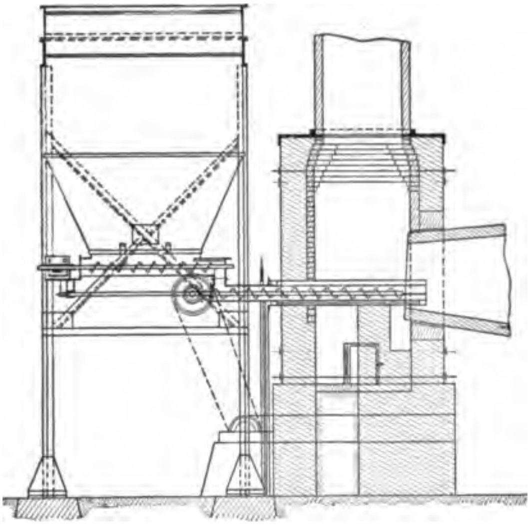


Fig. 52.—Kiln Feed by Jacketed Conveyer.

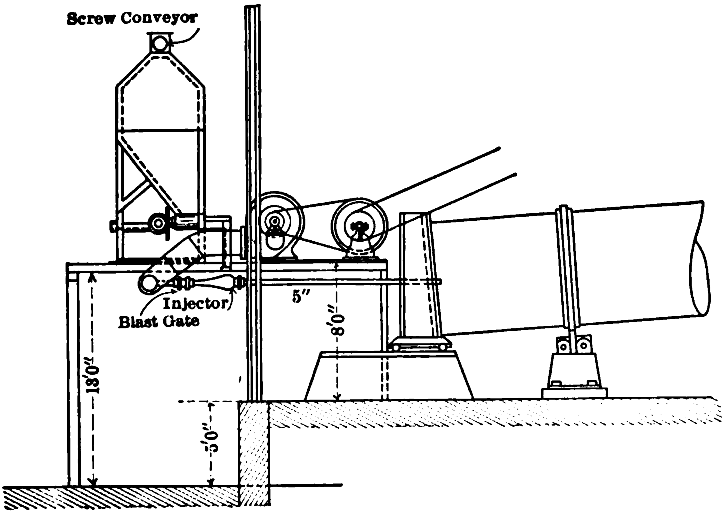
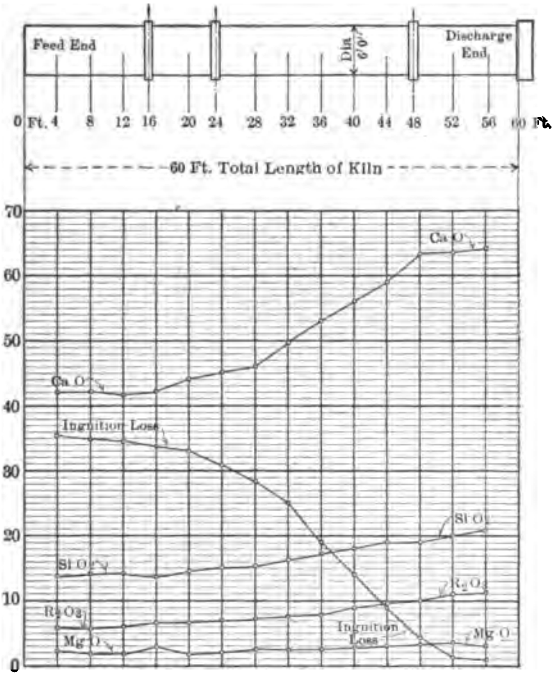


Fig. 53.—Coal Feed for Kiln.

duced. Natural-draft systems, whereby the coal is made to fall in a thin sheet across a slit in the end of the kiln, being carried in by the air sucked in by the natural stack draft, have also been introduced.

Crude oil, the use of which first made the operation of the rotary kiln a commercial success, is now used only in certain districts where its cost remains low while coal is high. When burned in the rotary kiln it is sprayed in by a blast of air from blowers or air compressors. In order to distribute properly the heat in the kiln two or more oil burners are used.



Chemical Changes in 60-Ft. Kiln

Fig. 54.

Natural gas is now used in only a few plants, situated for the most part in the State of Kansas. As the supply gradually diminishes it is being replaced by oil or coal. When burned in the kiln it is introduced in a manner entirely similar to the use of oil, a portion of the air required for combustion being used to inject the gas.

The operation of the rotary kilns requires at all times the attendance of a skilled burner who may look after from two to four kilns. The fuel supply and the speed or rotation, and hence the temperature of the kiln and degree of burning of the clinker, are under the direct control of the burner. The heat is judged simply by the incandescence of the interior (viewed through darkened glasses) and the degree of burning of the clinker, as well as the temperature found by experience to be best under any special plant conditions, are maintained as uniformly as possible.

Proper burning is determined by the color and appearance of the clinker, the properly burned clinker being a greenish black in color, having a vitreous luster and showing bright glistening specks when just cooled. The lumps are, in the main, from a size of a walnut down. Under-burned clinker is brown or has brown centers, and lacks the luster of well-burned clinker. Over-burned clinker has hard brown centers. Over-burned clinker is probably not injurious except for very low lime cements, but over-burning means a fuel waste, and the grinding expense will be increased owing to the greater hardness of over-burned clinker.

The nature and sequence of the chemical changes which take place in the kiln has been noted above, Art. 89. Fig. 54 graphically represents the nature of the changes during burning, as determined by experiments made by Wm. B. Newberry, who analyzed the contents of a 6 by 60-foot kiln during a temporary shut-down. Similar experiments made on longer kilns show that the extra length accomplishes practically nothing except the driving off of the moisture in the raw material and heating up the material to the dissociation temperature of the carbonates, heat that would otherwise be carried off by the flue gases being thus utilized. Under good average conditions an 8 by 100-foot kiln should turn out about 600 barrels of cement per day with a fuel consumption of about 80 pounds of coal per barrel. A 9 by 150-foot kiln should turn out about 750 barrels per day.

An idea of the sources of heat and the utilization of same in the rotary kiln is conveyed by the following approximate estimate:

SOURCES OF HEAT

Heat from combustion of coal	71.8 -84.7	per cent
Heat from mix, coal, or air	0.0 -10.8	per cent
Heat from chemical combination	9.0 -17.4	per cent

HEAT UTILIZATION

Heat used in evaporating water	0.15- 1.7	per cent
Heat used in dissociation of sulphates	0.33- 0.76	per cent
Heat used in dissociation of carbonates	19.6 -25.0	per cent

HEAT LOSSES

Heat lost with hot clinker	10.7 -15.5	per cent
Heat lost with stack gases and flue-dust	43.6 -51.4	per cent
Heat lost by radiation and combustion	11.2 -15.4	per cent

The low heat efficiency attained in the rotary-kiln calcination of cement has led to a quite general effort to devise means of utilization of the waste heat.

Heat lost by radiation cannot by any means be utilized, but may only be reduced as much as possible by the placing of a poor heat conductor between the kiln lining and the shell. Heat carried away from the kiln in the stack gases may be reduced in some degree by lengthening the kiln, thereby utilizing a part of this heat in drying and preheating the raw material in the upper part of the kiln.

The utilization of the heat carried by the stack gases has been tried out in two ways: the first and most common method is by using these gases for the drying of the raw material in rotary dryers, the second method consists in passing the gases through vertical water-tube boilers, thus generating steam for the operation of the power plant. Both methods have been fairly successful and promise in time to be more generally adopted. The principal difficulty encountered is the presence of large quantities of dust in the kiln gases, which makes impossible most ordinary methods of heat regeneration.

The utilization of the heat carried off by the hot clinker is quite common in German practice and is becoming more so in this country. In general the method applied consists in drawing the air used for combustion in the kiln through the hot clinker in a rotary cooler, thus cooling the clinker and preheating the air.

93. Treatment of the Clinker, Cooling, Grinding, and Pulverizing. The clinker as it issues from the kiln is very hot, and must be reduced to a suitable temperature before being ground. Occasionally it is the practice of cement plants to allow the clinker to cool in piles outside the mill. More generally, however, it has been found advisable to adopt some type of mechanical cooling device which may or may not provide for the recovery and utilization of the heat carried off by the hot clinker.

It is the usual practice to grind the clinker by the same type of grinding machinery used in the raw-material mill, the grinding and pulverizing being practically invariably done in two separate stages. The principal systems are therefore:

1. Ball mill, kominuter, or rolls, followed by a Fuller-Lehigh mill.
2. Ball mill, kominuter, Griffin mill, Kent mill, Sturtevant mill, or Huntington mill followed by tube mill.
3. Series of rolls.

94. Addition of Retarder. The clinker produced in the rotary kiln process makes a cement which is naturally very quick setting because of its high lime content. In order, therefore, to retard its set sufficiently to enable it to meet commercial requirements, it is the universal practice to add sulphite of lime either before grinding or between the stages of grinding and pulverizing the clinker. The retarder was at one time added in the form of plaster of Paris ($CaSO_4+\frac{1}{2}H_2O$). Now, however, the universal practice (with the exception of a few plants which add plaster of Paris after pulverizing the clinker) is to add raw gypsum ($CaSO_4+2H_2O$). The gypsum is obtained in the form of lumps crushed to pass a 1-inch ring and is added to the clinker either by hand or by mechanical weighing devices, the quantity used being, as a rule, about 2 per cent, and never exceeding 3 per cent. The retarding agent is the sulphur trioxide present, whether plaster or gypsum be used, and the more frequent choice of the latter is due entirely to the advantage in cost of crude gypsum over that of the dehydrated form.

95. Storing and Packing. The finished cement is stored in stock-houses containing bins holding from 1000 to 5000 barrels each. The bins usually discharge to hoppers and screw conveyors in tunnels below each row of bins.

Cement is either packed in wooden barrels containing 380 pounds, or in cloth or paper bags containing 95 pounds net. Packing is commonly done by some type of semi-automatic machine (Fig. 55), which fills, weighs, and seals the barrels or bag. Cloth bags are now almost exclusively used.

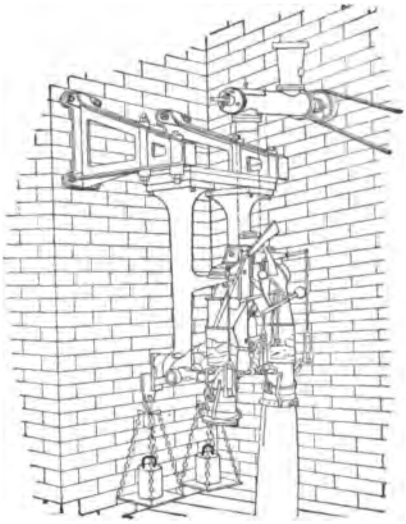


FIG. 55.—Automatic Packing Machine.

THE WET PROCESS

96. The Wet Process of Manufacture, Using Marl and Clay or Shale. In American practice only one class of raw materials is handled by the wet process—mixtures of marl with clay or shale. In English and German practice chalk and clay are often handled by wet-process methods. In general the materials so handled are those of a soft physical character, and which in their natural state carry high percentages of moisture.

Marl is usually not only saturated with moisture, but is often covered with water to a considerable depth. Under such circumstances it is obtained by dredging. Usually the excavator is carried on a barge which floats in a channel formed by the dredge in its progress through the basin. The material excavated may be loaded by the dredge upon cars running on tracks alongside the dredged channel, and thence be carried to the mill, or in some cases the material may be loaded by the excavator into hoppers which feed a pug mill, wherein the marl is mixed with additional water so that it may be pumped to the mill through a pipe line. The marl usually reaches the plant in the shape of a thin mud containing about 50 per cent water. It is passed through a separator to remove stones, roots, etc., and then stored in large cylindrical tanks.

The clay upon arrival at the plant is often dried in order to facilitate the determination of the correct proportion to be added to the marl. It is then ground in an edge runner mill (Fig. 56), between mill-stones, or in a disintegrator.

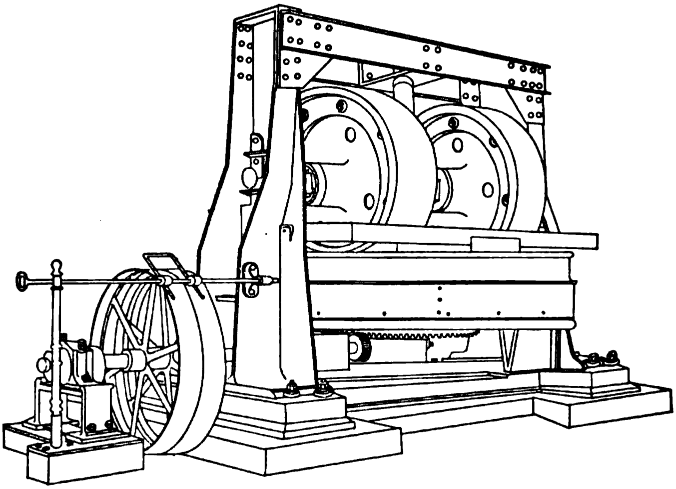


FIG. 56.—Edge Runner Mill.

From the storage tank the marl is pumped either into a measuring tank or a weighing hopper. The ground clay is delivered to bins above, and added to the marl in the proportion determined by analysis of the materials.

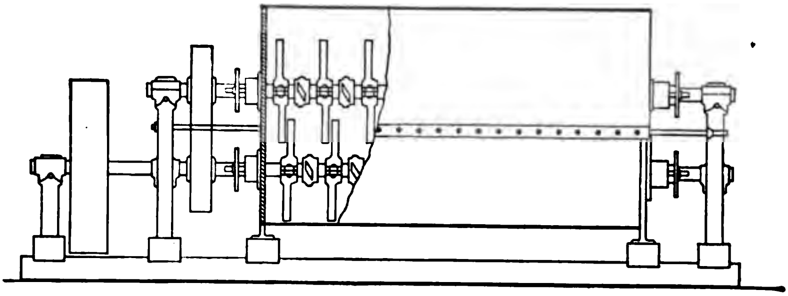


FIG. 57.—Pug Mill.

The mixture is now discharged into a pug mill, Fig. 57, which consists simply of a horizontal cylinder within which two shafts provided with steel propelling blades rotate. The mixture is churned up by the revolving blades, thoroughly mixed, some additional water being usually admitted, and discharged into large vats or dosage tanks where it is sampled, analyzed, and the mixture corrected by the addition of the correct amount of clay and marl. In order to prevent any part of the mixture from settling, it is necessary to provide these tanks with revolving arms with paddles which keep the mass constantly agitated.

The slurry is now passed on to final grinding, which is usually done either in a wet-emery mill or in a wet-tube mill.

The output of the finishing mill is conveyed to supply tanks for the kilns and is charged in without any previous drying. It usually contains, therefore, from 60 to 65 per cent of water which must be evaporated in the upper part of the rotary kiln. This practice necessarily increases the fuel consumption of the kiln, but has been found to be more practical than the drying of the mixture in a rotary dryer prior to calcination.

The production of Portland cement by the wet process, using marl and clay, has steadily decreased for several years, many plants finding it advantageous to substitute limestone for marl and use the dry process.

97. The Wet Process, Using Chalk and Clay. The chalks and clays utilized in Germany and, more particularly, in England, for the manufacture of Portland cement, usually contain from 20 to 30 per cent water, and the favorite method of reduction of the material is by the use of a series of wash mills (Fig. 58).

The clay and the chalk are sometimes separately ground in wash mills which subsequently discharge into a common wash mill. Particularly is this the case if one material is considerably more refractory than the other. Commonly, however, both materials are discharged into one mill in the desired proportion.

Gratings placed at intervals around the periphery of the pits allow the slurry to be washed gradually from one mill to the next. Three or four mills are commonly used, the material becoming finer with each successive pass.

The quantity of water used in the operation of the wash mill is sometimes only sufficient to make a thick slurry, 40 to 45 per cent water; in other cases it is sufficient to make a very thin slurry, carrying about 80 per cent water. When the thin slurry is used settling basins are usually provided from which the water can be drawn off at intervals, the mass remaining being usually dug out and briquetted for use in stationary kilns.

The wash mill operated with 40 to 45 per cent water leaves the material in a state of subdivision sufficient to pass about 90 per cent through a 100-mesh sieve, the residue consisting largely of comparatively large nibs of calcium carbonate which, if not removed or further ground, would mean the presence of free lime in the manufactured product. It is therefore the common practice in the more modern European plants using the wash mill, either to separate out these large particles by use of a sifting device or to further reduce the material by grinding with either mill stones, emery mills, or wet-tube mills, the latter practice being the more commonly employed.

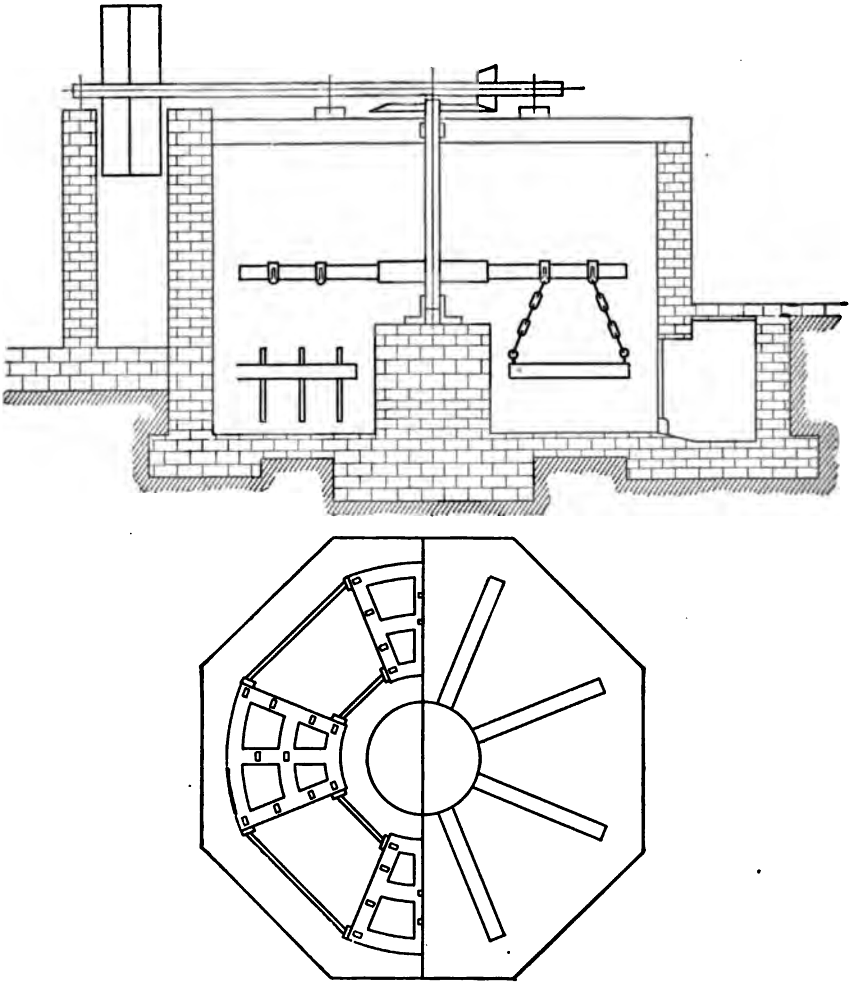


FIG. 58.—Wash Mill.

SEMI-DRY PROCESSES

98. Semi-dry Processes. In a few instances both here and in Europe the wet-slurry process of handling raw materials has been applied to dry raw materials such as limestone and shale, etc.

The pulverized raw materials are passed to a pug mill, the mix corrected in dosage tanks, and the wet slurry fed to rotary kilns, as in the wet process. The only justification for such treatment is the availability of cheap kiln fuel such as crude oil or natural gas. Under such conditions some saving may be effected, since an intimate mixture of the constituents is procured without such fine grinding as is required for the dry process. Where coal fuel must be used, the saving in the grinding department is more than offset by the extra fuel requirement of the kiln for drying the slurry, and the only advantage remaining lies in the fact that as in the wet process, the composition of the mix is under better control than in the dry process.

CEMENT MILL EQUIPMENT

99. Equipment of Raw Mill. *Rock Crushers.* Crushers employed in the initial reduction of the quarry output are either jaw crushers or rotary gyratory crushers. In the first type of crusher (Fig. 38) the reduction is accomplished between a fixed jaw and a hinged reciprocating jaw. In the latter type (Fig. 39) the material falls within a hopper-shaped chamber lined with concave corrugated plates mounted concentrically with the crushing head. The latter is a corrugated steel cone widening toward the bottom, where the annular space between the cone hopper and the crushing head is only large enough to permit the passage of material of a predetermined size. The crushing head is rotated through an eccentric drive which imparts to it an oscillating motion and thereby lessens the liability of choking.

A third class of crusher used for primary reduction consists of two horizontal rolls made to rotate in opposite directions and provided on their periphery with corrugations or large teeth. The best-known crushers of this class are the Edison rolls (Fig. 40), the cylindrical surfaces of which consist of studded plates which grip and crush the rock. In the more recently designed Edison rolls there are provided at two diametrically opposite points on one roll a row of "sluggers," or unusually high knobs, which shatter large rocks sufficiently to bring their size within the angle of grip of the rolls. The capacity of the larger sized Edison rolls is so great that quarry stone up to 7 feet in thickness may be handled.

Dryers. The type of dryer used in cement mills almost exclusively is the rotary dryer. This device (Fig. 41) consists of a cylinder, 5 to 7.5 feet in diameter, and 40 to 60 feet long, set on a slight inclination, and rotated slowly on roller bearings. The material fed in at the upper end passes slowly through to the discharge end by gravity. Often the interior wall of the dryer is provided with angle irons bolted on parallel to the axis of the cylinder for the sake of facilitating the drying process by lifting and dropping the material as the cylinder revolves. The dried material escapes from the lower end of the cylinder into a conveyor or elevator whereby it is transported to the grinding mills.

The rotary dryer is heated either by the direct combustion of fuel in a furnace located at the lower end of the cylinder, or by the waste gases from the cement kilns. In either case the hot gases pass through the length of the dryer, escaping up a stack set at the upper end. The use of pulverized coal in a manner similar to its use in the rotary kiln has lately been introduced.

For drying some classes of material which normally carry very high percentages of water, double-heating dryers are sometimes used. The Ruggles Coles Dryer (Fig. 41*a*) is perhaps the best-known dryer of this type. It consists of two concentric cylinders fastened together and revolved on roller bearings. The inner cylinder connects with a furnace at the upper end and is open at the lower end. A fan blower is used to exhaust the gases from the annular outer chamber at the upper end, the path of the gases being therefore down through the central flue and back through the space between the cylinders. The material to be dried is fed in between the cylinders at the upper end, and is caught up by flights on the inside of the outer cylinder and dropped on the hot inner shell. As the cylinder revolves this action is repeated, the drying being further hastened by the hot gases passing through the outer chamber.

The fuel consumption of the rotary dryer is greatly dependent upon the amount of water carried by the material and the character of that material. Marls, because of their high content of organic matter, are especially retentive of moisture. In general the fuel requirements of the dryer vary from about 1 pound of coal per 5 pounds of water evaporated, under the most unfavorable conditions, to about 1 pound of coal per 7 or 8 pounds of water evaporated under favorable conditions.

Grinding Machinery. Centrifugal Grinders and Ring Roll Mills. The Griffin mill (Fig. 46) consists essentially of a steel ring or die against the inside surface of which a heavy steel crushing roll, mounted on a pendulum suspended from a universal joint, is made to roll by centrifugal force. The pendulum is rotated by a pulley at the top and the crushing roll is provided with plows which throw back into the grinding zone the material which has passed the roll into the pit below. The fan mounted upon the pendulum shaft above the roll facilitates the passage of the sufficiently fine material through the annular screen placed just above the grinding zone. The Griffin mill will turn out 8 to 10 barrels of raw material per hour ground to pass about 95 per cent through the 100-mesh sieve.

The three-roll Griffin mill or Bradley mill (Fig. 47) is a modification of the usual Griffin mill, resembling it in every respect except that the single crushing roll is replaced by three rolls.

The Huntington mill (Fig. 48) is somewhat similar to the three-roll Griffin mill. It is used only in the plants of one large manufacturer. Three heavy crushing rolls are freely suspended from a circular revolving spider. As the head revolves the rolls swing outward through the action of centrifugal force, pressing against an annular die-ring of steel. On raw material the output of the Huntington mill will be from 15 to 25 barrels per hour ground to pass 93 per cent through a 100-mesh sieve.

The Raymond impact pulverizer resembles the Bradley and Huntington mills except in its detail design.

The Kent mill (Fig. 59) and the Maxecon mill, which latter is simply an improved machine employing exactly the principles of operation of the Kent mill, are ring-roll mills which in some respects resemble the Griffin and Huntington mills, but which employ powerful springs instead of centrifugal force for the grinding pressure. Three convex-faced rolls are mounted on equidistant horizontal axes within the grinding ring. One roll is power driven, and this rotates the ring by traction, the latter in turn rotating the other two rolls. The output of the mill is separated by an auxiliary sifting mechanism, the mill itself having no separating device, and the coarser portion is returned for further grinding.

The Sturtevant ring-roll mill operates in a manner similar to the Kent mill except that the die is positively driven and not through traction by one of the rolls.

The class of mill in which a number of balls are driven around a horizontal annular die is a special type of ring-roll mill. The Fuller-Lehigh mill (Fig. 45) is perhaps the best-known mill of this class. Four balls, weighing 100 pounds each, are impelled around the grinding ring at a speed of 600 feet per minute, by arms secured to a vertical spindle. They press against the grinding ring through centrifugal force. The material is fed into the center of the mill, forced by a fan into the grinding chamber, and the fine material expelled through sieves protected by grids. The output of the mill on raw material is from 20 to 30 barrels per hour ground to pass 95 per cent through a 100-mesh sieve. An unusually high proportion of this material will pass a 200-mesh sieve.

Rotary Attrition Mills. Ball Mills, Kominuters, and Tube Mills. The ball mill (Fig. 42) is a short drum rotated at a rate of 20 to 30 revolutions per minute about a horizontal axis, the interior surface being so formed that it consists of a series of steps. The drum contains a number of large steel balls which roll and fall from step to step, thereby crushing and grinding the material fed in through one axis. The stepped plates are perforated, and the material, when sufficiently ground, passes through the perforations onto a screen and finally onto a second screen. The particles too coarse to pass the screens are returned to the grinding chamber through the openings between the overlapping grinding plates. Material which passes the screens will escape into the hopper below and thence to the conveyors. The output is 15 to 24 barrels per hour, to pass a 20-mesh screen.

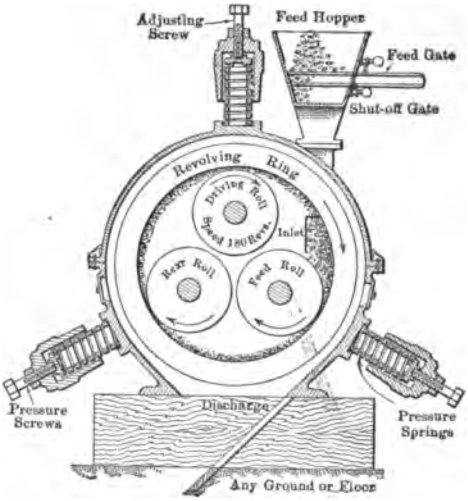


FIG. 59.—Kent Mill.

The kominuter (Fig. 43) is a modification of the ball mill, the principal point of difference being that the grinding plates are not stepped or perforated and the material must pass the length of the drum to an outlet provided at the further end, where it drops on a screen outside the grinding plates. These screens being conically shaped, slope toward the inlet end, and discharge the over-sized material back into the drum at the center of the inlet end. The material sufficiently ground escapes in the same manner as in the case of the ball mill. The kominuter is capable of grinding 20 to 30 barrels of raw material per hour to a size to pass a 20-mesh screen.

The tube mill (Fig. 44) resembles the ball mill and kominuter in that it is a rotating cylinder partially filled with an abrasive agent. The tube mill is, however, much longer than the ball mill or kominuter. It is usually employed for final reduction of the product of mills of another type.

The tube mill consists of a steel cylinder, 5 to 6 feet in diameter, and 20 to 22 feet long, lined with hardened plates or hard natural stone and mounted on trunnions about which it is slowly revolved at a rate of 25 to 30 revolutions per minute. The abrasive charge usually consists of flint pebbles which fill it approximately to the axis of rotation. The material is fed in through a hollow axis at one end, and either escapes in a similar manner at the opposite end through a hollow axis and screens, or is allowed to escape through gratings at the periphery of the discharge end. Steel balls are occasionally substituted for flint pebbles as the abrasive agent. The fineness of grinding is regulated by the rate of feed, and the capacity for a 5 by 22 foot mill is about 12 to 20 barrels per hour ground to pass 95 to 98 per cent through a 100-mesh sieve. The wet tube mill differs in no essential respect from the dry-tube mill except that the discharge is usually through a screened drum located axially, rather than through perforations located on the periphery of the discharge end.

The Edge Runner Mill. The edge runner mill (Fig. 56) consists of a cast-iron shallow pan in which a pair of wide-tired cast-iron rollers revolve by traction as the pan is rotated, or else the central vertical shaft, which carried the rollers on cranks at right angles to its axis, is itself rotated, the pan being stationary. This latter type is less common. The edge runner mill may be arranged to work with either wet or dry material provided only that the material be of a not too refractory nature. The material is fed into the pan in front of one of the rolls and, after passing the roll, is diverted by scrapers to the perforated plates which surround the pan, then by scrapers again diverted to the pan in front of the other roll, and so the process continues, the size of the output being dependent upon the perforations of the plate, usually being not much under $\frac{1}{4}$ inch, though sometimes under $\frac{1}{20}$ inch. The output of $\frac{1}{4}$-inch material for a 5-foot roll machine working on shale is about 6 tons per hour. The millstones, the rock-emery mill, and the other types of grinding machinery used in the wet process with marl and clay have been described above. (Art. 64.)

100. Cement Kilns. *Early Kilns.* The earliest type of kiln used for cement burning both in Europe and America was an upright stationary-shaft kiln called a dome kiln or "bottle" kiln (Fig. 60), which closely resembled the kilns used for lime burning. The fuel and the raw slurry molded into bricks were charged in at the top and the clinker was withdrawn at the bottom, the process being intermittent. The clinker required hand sorting to separate out the over- and under-burned material. The fuel consumption was high, and the demand for hand labor in molding the brick and sorting the clinker, excessive.

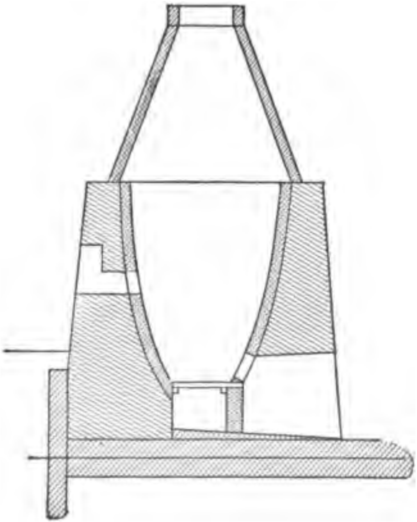


Fig. 60.—Dome Kiln.

The first efforts to improve the efficiency of the dome kiln were in the direction of utilization of the hot waste gases of the kiln for the drying and preheating of the raw material. The Johnston kiln attempted to make this saving by a simple arrangement whereby the waste gases of the kiln were led through a long flue within which the briquetted material was sorted and dried. The kiln was still wasteful of fuel in consequence of the fact that its operation was intermittent.

The Hoffman or ring kiln (Fig. 13), which has been described in connection with the discussion of lime burning, was next utilized in the cement industry. It is very economical of fuel, but requires an excessive amount of skilled hand labor in molding the bricks and charging the kiln. The Hoffman kiln is still in operation in a few German cement plants in districts where labor cost is very low and fuel cost very high.

The Dietsch shaft kilns (Fig. 61) and the Schöfer kilns (Fig. 62) consist of a long vertical flue terminating in a stack, the lower portion of which serves as a preheating chamber for the dried slurry briquettes which are charged with the fuel. A chamber below the preheating chamber serves as a combustion chamber, and the lower portion serves as a cooling chamber for the clinker, the incoming air for combustion being heated thereby.

The shaft kilns are the most economical of fuel of any type of kiln, but they all suffer under the disadvantage of requiring the briquetting of the raw material and the sorting out of the under-burned and over-burned clinker by hand. The fuel consumption is only about 45 pounds of coal per barrel, but the labor cost is excessive. The shaft kiln is still in use to a limited extent in Europe, but even in Germany, where economic conditions are most favorable to their use, the ring kiln and the shaft kiln have been replaced in two-thirds of the plants by the rotary kiln.

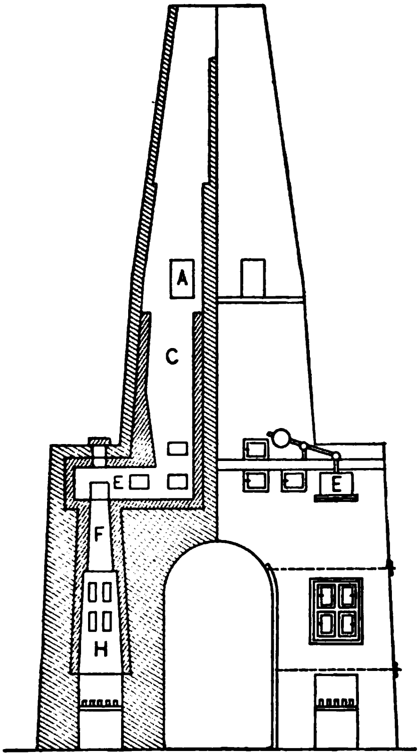


FIG. 61.—Dietsch Shaft Kiln.

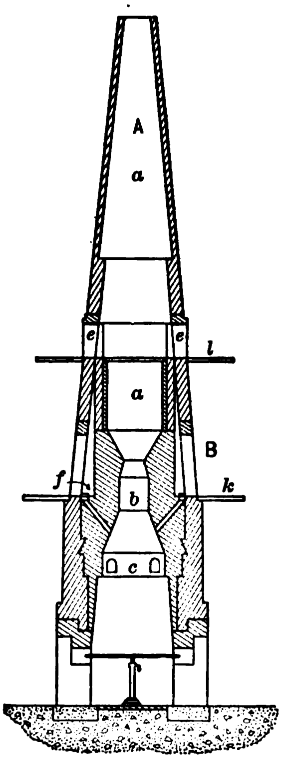


FIG. 62.—Schöfer Kiln.

The Rotary Kiln. The modern rotary kiln (Fig. 50) consists of a cylindrical steel shell lined with refractory material and supported on rollers, its axis being slightly inclined from the horizontal. It is revolved on its bearings by a variable speed transmission; its upper end projects into the chimney foundation, which also serves as a dust trap; its lower end enters a movable hood adapted to the discharge of clinker and the entry of fuel and air. Pulverized coal injected by an air blast is most commonly used as fuel, although crude oil is used in plants whose output total about 15 per cent of the output of the United States, and natural gas fuel is used in the production of about 5 per cent of the total.

The first rotary kiln was patented in 1885 in England by Ernest Ransom. It was first made a commercial success in this country, however, the fuel used being petroleum. The use of powdered coal as a fuel was introduced in 1895, from which time the remarkably rapid growth of the industry dates.

Rotary kilns in use to-day vary in size from 60 feet long and 5 feet in diameter to 240 feet long and 12 feet in diameter. Present practice, however, favors the use of the longer kilns, and few are now installed less than 125 feet long by 8 feet in diameter, and 150 feet long by 10 feet in diameter seems to be about the present standard size for new installations. The kiln is inclined at a pitch varying from ½ to ¾ inch per foot of length, and is supported by rollers bearing on wide steel tires at from two to five points in the kiln length, the number of supports depending upon this length. Two or more horizontal thrust rollers keep the inclined kiln in place on its bearings. In general the rate of rotation is from one-half to two-thirds of a revolution per minute, though in some cases the rate is as low as one-eighth revolution per minute, and in other cases as high as one or even, in rare cases, two revolutions per minute. The rate of revolution depends upon the slope of the kiln and the nature of the raw material.

The lining of the kiln is usually a highly refractory magnesite or bauxite brick, but in a few instances linings of fire clay or of brick made from Portland cement clinker and Portland cement have been used. The thickness of the lining is variable, being usually from 9 to 12 inches at the lower and hotter end, and 4 to 6 inches at the upper end. In some kilns burning wet slurry the upper part of the kiln is left unlined. The brick are keyed to fit the circle of the kiln, and are held in place by the heavy angle iron which encircles the inside of each end of the kiln.

The hood at the lower end of the kiln is usually mounted on a movable carriage, and the masonry of its front wall is provided with two openings, one for the entrance of the burner apparatus, the other for observation of the operation of the kiln and the insertion of bars for breaking up rings of clinker and making minor repairs to the lining.

The lower part of the hood is left partly open to allow the escape of the clinker, which is either diverted to one side into cars, or falls directly onto conveyers. This opening also serves as an air inlet.

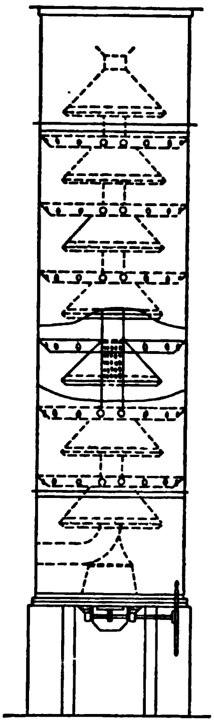


Fig. 63.
Vertical Clinker Cooler.

101. Clinker Cooling Equipment. Equipment of Finishing Mill. Many of the older plants use an upright gravity cooler (Fig. 63) consisting of a cylinder about 8 feet in diameter and 35 feet high, provided with baffle plates and shelves. The hot clinker is discharged into an elevator pit, where it is sprinkled with water; the elevator discharges it into a hopper at the top of the cooler, whence it falls down over the series of baffles, where it encounters air currents introduced through a perforated vertical pipe in the center of the cooler. A hopper at the base discharges the cooled clinker to a conveyor.

More modern mills employ a rotary cooler (Fig. 64) which consists of a steel cylindrical shell mounted on rollers in a slightly inclined position and rotated slowly in a manner similar to the operation of the rotary dryer. The rotary cooler is often mounted as an under-cooler directly below the kiln for convenience in direct discharging of the clinker from the kiln to the cooler, the cooling air being drawn into the kiln. The cooler lining consists usually of cast-iron plates bolted to the shell, and shelves are usually provided as in the dryer for the purpose of lifting the material. Water to help cool the clinker is sometimes introduced at the upper end of the cooler and perforations in the shell during the lower 3 feet of its length, 1¼ to 2 inches in diameter, screen the material roughly. An angle iron with the flange projecting inward at the discharge end of the cooler forces the material to escape only through the perforations.

FIG. 64.—Rotary Coolers Mounted beneath Kilns.

Sometimes the rotary cooler is mounted separately from the kiln, and in such an event it is not usually used to preheat the air for the kiln, but the current of air is drawn through by a stack or blown through by a fan.

The grinding equipment of the finishing mill is, as above noted, usually a duplicate of that used in the raw material mill. The reason for this circumstance is the fact that if the same types of machines are used in both mills only one line of repair parts need be carried.

102. Cost of Manufacture. Manufacturing costs are dependent upon many factors, among which may be mentioned the cost of labor, the character and availability of the raw materials, the plant equipment and management, and the plant location with respect to transportation facilities. Cost figures are naturally difficult to obtain for any individual plant. In general, however, it may be said that the cost per barrel at the plant is rarely below 55 to 60 cents per barrel, and in many plants such a figure cannot be approached.

103. Production of Portland Cement. The statistics quoted in Art. 74 give the production of Portland cement in the United States in the last forty years. It will be noted that the industry showed a fair but not remarkable growth from its commencement until 1895, when coal burning in the rotary kiln became commercially successful. From that time the growth of the industry has been uniformly rapid and continuous, with the exception of the years affected by the financial crisis of 1907. For the past few years the growth has averaged from 15 to 20 per cent per year, a rate of increase that no other industry of equal magnitude can approach.

PROPERTIES AND USES OF PORTLAND CEMENT

104. General. The value of cement as a structural material depends primarily upon its mechanical strength when hardened. The conditions met with in practical use are, however, necessarily so variable as to exclude the possibility of the establishment of standards directly based upon practical experience.

The establishment of the existing standards for physical and mechanical properties has for its object the fixing of values of certain properties, readily determined in the laboratory, for cements found satisfactory in practice, in order that inferiority in any particular cement may be detected by deviation from such standards.

Therefore the results of all laboratory tests of cement cannot be considered to represent the properties of the material under the conditions in which the cement is used in structures, but merely the properties shown under certain standardized conditions, the quantitative results obtained having only a relative value.

The physical properties so utilized for comparative purposes are: specific gravity, fineness, time of setting, and soundness. The mechanical properties similarly used are the tensile and compressive strength in neat cement mixtures and in sand mortars.

105. Composition of Portland Cement. A study of a large number of analyses of commercial cements reveals the fact that the range in possible composition is comparatively limited. For the purpose of showing graphically the extent of the possible variation in composition of Portland cements, Figs. 65 and 66 are introduced. These figures are constructed upon the basis of the following table, which is a summary of detailed analyses of eighty samples of American Portland cement (representing forty-three brands) quoted by Eckel.

Component.	Ave. of 80 Samples. Per cent.		Ave. of 5 Highest Brands. Per cent.		Ave. of 5 Lowest Brands. Per cent.	
	Actual.	Equiv.	Actual.	Equiv.	Actual.	Equiv.
SiO_2	21.83	(22.34)	24.21	(24.29)	19.69	(20.49)
Al_2O_3	7.43	(7.61)	9.54	(9.69)	4.67	(4.79)
Fe_2O_3	3.31	(3.39)	4.99	(5.12)	1.95	(2.00)
CaO	62.57	....	65.06	....	59.22	
MgO	1.85	....	3.34	....	0.45	
CaO+1.4(MgO)	65.14	(66.66)	68.27	(68.40)	61.77	(64.80)
Alk.	1.15	....	1.93	....	0.55	
SO_3	1.33	....	2.39	....	0.39	

Of the compounds included in the above table the alkalies and anhydrous sulphuric acid may be omitted in the discussion of the composition of cement, their amounts being small and, moreover, somewhat arbitrarily limited by practical considerations.

Magnesia cannot be neglected, but by the consensus of opinions of most authorities we are safe in assuming that magnesia may be considered equivalent to lime in its action, due allowance being made for the difference in their combining weights. (The atomic weight of Ca being 40.1, Mg, 24.3, and O, 16, the relative combining weights will be $CaO \div MgO = 56.1 \div 40.3 = 1.4$.) Figures expressing lime+equivalent magnesia have therefore been added in the above table.

We have, therefore, four constituents of cements to consider—silica, alumina, iron oxide, and lime+equivalent magnesia. If, now, we consider the average percentages of all constituents, we find they do not total 100 per cent, and the original figures are therefore corrected on the basis $SiO_2+Al_2O_3+Fe_2O_3+CaO+1.4MgO=100$ per cent, and have been placed in parentheses in the column adjoining the original figures.

In the second division of the table are given the average percentages of each constituent for the five brands averaging highest for that particular constituent. Similarly in the third division are given the percentages for the five brands averaging lowest for each particular constituent. The figures placed in parentheses in the second and third divisions of the table have been computed from the complete analyses of each of the five cements whose average is expressed by one of the original figures. The manner of derivation of the corrected percentages may best be explained by an example: For instance, the figure 24.21 in the second division of the table represents the average percentage of silica for the five cements which ranked highest in silica. The average amounts of Al_2O_3, Fe_2O_3, CaO, and 1.4 MgO in these same five cements were similarly computed, and the percentage of silica corrected on the basis of the total amount of $SiO_2+Al_2O_3+Fe_2O_3+CaO+1.4MgO=100$ per cent. The corrected percentage of silica was thus found to be 24.29 per cent. By similar computations the remaining figures in this column and the last column of the table were obtained.

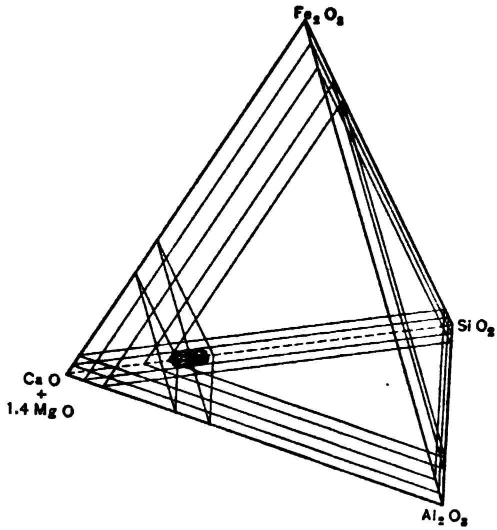


FIG. 65.—Composition of Portland Cement.

The construction of the diagrams of Figs. 65 and 66 is dependent upon the geometrical principle that the sum of the normals from any point within an equilateral tetrahedron to the four sides is equal to the normal from a vertex to the opposite side. We designate the four vertices to represent 100 per cent $CaO+1.4MgO$, 100 per cent SiO_2, 100 per cent Al_2O_3, and 100 per cent Fe_2O_3, respectively. Then any chosen point within the tetrahedron represents a compound or mixture having certain definite percentages of each of the four constituents (i.e., the percentage of lime will be represented by the ratio of the normal from the chosen point upon the Al_2O_3-SiO_2-Fe_2O_3-plane to the altitude of the tetrahedron, the percentage of Fe_2O_3 by the ratio of the normal upon the CaO-Al_2O_3-SiO_2-plane to the altitude, etc.) The maximum and minimum percentages for each constituent as given in the

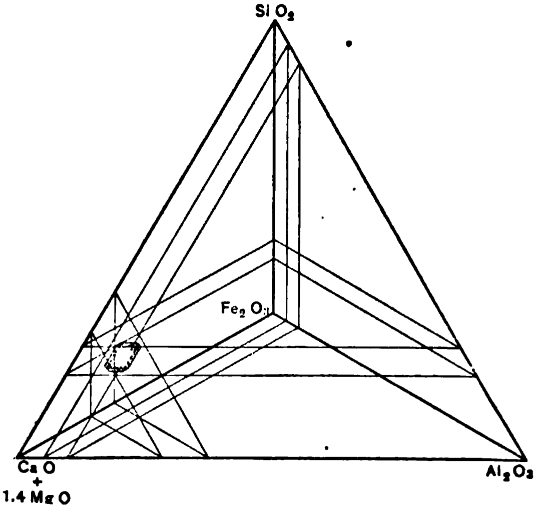


FIG. 66.—Composition of Portland Cement.

above table are therefore represented in the diagram by two planes, each being parallel to the side of the tetrahedron opposite the vertex which represents the constituent in question. The solid body represented in perspective in Fig. 65 and in plan in Fig. 66 is the portion of the tetrahedron CaO, Al_2O_3, SiO_2, Fe_2O_3 occupied by the field of Portland cement.

106. The Constitution of Portland Cement. Chemical analysis suffices for the determination of what chemical elements are present in cement and their relative percentages. It will not, however, ascertain in what manner these elements are combined, that is, the constitution of the cement.

The solution of the problem of the constitution of Portland cement has been the goal of much scientific research for many years past, but only during the last few years has the investigation been pursued along lines which could promise ultimate solution. Chemical analysis being of no avail, there remain two possible methods of investigation—microscopic and synthetic.

Microscopic investigation of cement clinker was first attempted successfully by H. Le Chatelier (1883), who applied to the study of cement clinker the methods employed in petrography in the study of rocks. Sections of clinker were reduced to such a degree of thinness by careful grinding that they became sufficiently transparent for microscopic examination by transmitted light. A later modification of this method more easily employed consists in polishing a single surface only of the specimen, developing the structure by etching with a suitable reagent, and examining by reflected light. A third method consists in examining powdered clinker by transmitted light, the powder being held in some transparent medium.

Le Chatelier and subsequently Törnebohm independently discovered four different kinds of crystals by microscopic examination of clinker. These were named by the latter Alit, Belit, Celit, and Felit. Clifford Richardson, who has made a similar study of clinker by microscopic methods, has thus summarized the facts established:

" Alit is the preponderating element and consists of colorless crystals of rather strong refractive power, but of weak double refraction. By this he means that alit in polarized light between crossed Nicol prisms has insufficient optical activity to produce more than weak bluish gray interference colors.

" Celit is recognized by its deep color, brownish orange. It fills the interstices between the other constituents, being the magma or liquid of lowest freezing-point out of which the alit is separated. It is strongly double refractive, that is to say, gives brilliant colors when examined between crossed Nicol prisms.

" Belit is recognized by its dirty green and somewhat muddy color, and by its brilliant interference colors. It is biaxial, and of high index of refraction. It forms small round grains of no recognized crystalline character.

" Felit is colorless. Its index of refraction is nearly the same as that of belit and it is strongly double refractive. It occurs in the form of round grains, often in elongated form, but without crystalline outline. Felit may be entirely wanting.

" Besides these materials an amorphous isotropic mass was detected by Törnebohm and Le Chatelier. It has a very high refractive index.

" Törnebohm adds the important fact that a cement 4 per cent richer in lime than usual consists almost entirely of alit and celit."

Synthetic investigations are not studies of actual kiln-clinker, but are studies of the product of burning definite artificial trial mixtures of pure lime, silica, alumina, etc. A complete synthetic investigation involves the determination of all the possible compounds, and eutectics (mixtures of two components in the particular proportion resulting in a mixture which exhibits a lower melting-point than other neighboring mixtures) which they form with one another in the two component systems (as $CaO—SiO_2$, $CaO—Al_2O_3$, etc.), and further, in the three and four component systems.

Le Chatelier and the Messrs. S. B. and W. B. Newberry made synthetic investigations so important that their work is still largely the foundation upon which the factory control of cement mixtures is based. Clifford Richardson later made synthetic studies of great importance, but the most valuable contributions to the knowledge of the constitution of Portland cement made during the last few years have been the results of the research recently completed by the physical chemists, physicists, and optical mineralogists connected with the Geophysical Laboratory of the Carnegie Institution in Washington.

Le Chatelier as a result of his investigations concluded that the essential constituents of Portland cement are: (1) Tricalcium silicate, $3CaO, SiO_2$; (2) tricalcium aluminate, $3CaO, Al_2O_3$; and (3) " a fusible calcium silico-aluminate whose chief function is that of a flux during burning to promote the necessary chemical reactions."

As has been noted above (Arts. 38 and 86), the Messrs. Newberry's conclusions as to the essential constituents of cement differed from those of Le Chatelier in that they believed that alumina occurred as the dicalcic aluminate, not as tricalcic aluminate. They agreed with Le Chatelier as to the occurrence of the tricalcic silicate as the other essential constituent.

The studies of the constitution of cement clinker carried on in the

Carnegie Geophysical Laboratory at Washington by Messrs. A. L. Day, E. S. Shepherd, G. A. Rankin, and F. E. Wright during the last few years constitute, as above noted, the most important contribution to our knowledge of the subject.

Three lines of investigation have been followed in the researches made in the Geophysical Laboratory: chemical, thermal, and optical. They are not independent, but overlap to some extent, the data from one serving to supplement or corroborate the results obtained by another method.

The behavior of lime, silica, and alumina was first exhaustively studied in the two-component systems lime-alumina, lime-silica, and silica-alumina, after which the investigation of the three-component system, lime-silica-alumina, was undertaken. In the study of the two-component systems no trace of the tricalcic silicate ($3CaO, SiO_2$), considered by all previous investigators to be an important constituent of clinker, was found. In the more recent work in the ternary system it has been found that a small addition of alumina brings out the tricalcium silicate, which appears to be a compound of very peculiar properties, becoming dissociated into lime and the orthosilicate below the melting temperature. In the presence of alumina, however, the fusion temperature is sufficiently reduced so that the compound can crystallize out of the melt and may therefore form an important part of cement clinker.

The work of the Geophysical Laboratory has established the possibility of the existence of five classes of cement clinkers:*

I.	II. Typical.	III.	IV.	V. Uncertain.
CaO	$3CaO, SiO_2$	$2CaO, SiO_2$	$2CaO, SiO_2$	$2CaO, SiO_2$
$3CaO, Al_2O_3$	$2CaO, SiO_2$	$3CaO, Al_2O_3$	CaO, Al_2O_3	CaO, Al_2O_3
$3CaO, SiO_2$	$3CaO, Al_2O_3$	$5CaO, 3Al_2O_3$	$5CaO, 3Al_2O_3$	$2CaO, Al_2O_3, SiO_2$

The four-component series, lime—silica—alumina—iron oxide, has not yet been investigated, nor has the truth of the assumption made by Eckel and others that magnesia may replace an equivalent amount of lime been established. A single magnesium aluminate was found to exist, having the formula MgO, Al_2O_3. No information was obtained bearing upon the question of the possible magnesium silicates. Magnesium metasilicates and orthosilicates, MgO, SiO_2 and $2MgO, SiO_2$, are known to exist, however.

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* Amer. Jour. Sci., Vol. 22, p. 301; Amer. Journ. Sci., Vol. 28, p. 293.

Messrs. Helpert and Kohlmeyer * have by a synthetic study of the binary series, lime—ferric oxide, established the existence of calcium ferrite, CaO, Fe_2O_3, and the tricalcium ferrite, 3CaO, Fe_2O_3. The former is formed with difficulty and is devoid of hydraulic properties; the latter is hydraulic.

It will be noted that the typical constitution as determined by the researches at the Geophysical Laboratory is in agreement with the conclusions of Le Chatelier except that the beta orthosilicate replaces Le Chatelier's "fusible calcium silico-aluminate." The dicalcic aluminate of the Newberrys was found to be non-existent.

The conclusions above quoted from the reports of Messrs. Day, Shepherd, Rankin, and Wright have been recently verified (1914) by Messrs. Rankin and Wright,† and have been independently verified by Messrs. Klein and Phillips of the Pittsburgh Laboratory of the U. S. Bureau of Standards.

As a result of the quite general acceptance which has been accorded the reports from the Geophysical Laboratory, it may be asserted with a considerable degree of positiveness that the typical constitution of Portland cement is:

Tricalcic silicate, 3CaO, SiO_2.
Tricalcic aluminate, 3CaO, Al_2O_3.
Beta orthosilicate, 2CaO, SiO_2.

Under certain conditions the orthosilicate may be lacking and free lime present, or, either the tricalcium silicate or aluminate or both may be lacking, and the 5 : 3 calcium aluminate or the monocalcic aluminate or both present.

107. Setting and Hardening. When a true hydraulic cement is gauged with sufficient water and then left undisturbed it soon loses its plasticity and finally reaches a state when its form cannot be changed without producing rupture. This change in condition is known as the "setting" of cement and has usually been considered somewhat distinct from "hardening." Setting usually takes place in a few hours or even minutes, while hardening may proceed for months or even years.

The successive theories which have been held regarding the setting of cement have been closely allied with the successive theories which have been held regarding the constitution of cement.

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* S. Helpert and E. Kohlmeyer, Ber. deut. chem. Ges., Vol. 42, p. 4581; Metallurgie, Vol. 7, pp. 193, 225.

† Messrs. Rankin and Wright have not yet published their final report. The above statement is based upon assurances privately communicated to the author by Mr. Rankin.

Le Chatelier considered that the tricalcic aluminate of lime in contact with water first became hydrated, the resulting crystallization explaining the initial setting of the cement. He ascribed the later hardening to the decomposition of the tricalcic silicate in contact with water resulting in the formation of hydrated monocalcic silicate crystals and calcium hydrate crystals, the progressive hardening being due to the growth and interlocking of the crystals.

Richardson later modified this theory in important particulars. According to his views the formation of lime silicates and aluminates during clinkering is only a convenient way of securing indirectly a very active lime hydrate which is itself the real cementing material.

" On the addition of water to a stable system made up of the solid solutions which composed Portland cement a new component is introduced which immediately results in a lack of equilibrium, which is only brought about again by the liberation of free lime. This free lime, the moment it is liberated, is in solution in the water, but owing to the rapidity with which it is liberated from the aluminate, the water soon becomes supersaturated with calcic hydrate, and the latter crystallizes out in a network of crystals which binds the particles of undecomposed Portland cement together. From the characteristics of the silicates and aluminates it is evident that the latter are acted upon much more rapidly than the silicates, and it is to the crystallization of the lime from the aluminates that the first or initial set must be attributed. Subsequent hardening is due to the slower liberation of lime from the silicates. If the lime is liberated more rapidly than is possible for it to crystallize out from the water, expansion ensues and the cement is not volume constant.

" The strength of the Portland cement after setting is due entirely to the crystallization of calcium hydrate under certain favorable conditions, and not at all to the crystallization of the silicates or the aluminates, since in this act of hydration nothing can take place which would tend to bind these silicates and aluminates together." *

The recent development of interest in the so-called " colloidal theory " of the late Dr. William Michaelis † offers another explanation of the setting and hardening of cement. According to Michaelis, " the calcareous hydraulic cements owe their setting mainly to the formation and desiccation of colloidal hydrated aluminum silicates, and their later hardening to the formation of colloids, calcium silicate and calcium hydroxide, the latter in the crystalline form."

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* Clifford Richardson, Eng. News, Vol. 53, p. 84 (1905).

† See Translation of Michaelis' latest work published by " Cement and Engineering News," 1909.

Michaelis supports his theory by the following argument based on volume constancy: The action of lime on silica and alumina in the presence of water leads to the formation of a gelatinous mass of variable composition. The absorption of water by the colloidal mass is accompanied by a great increase in the volume of the individual particles of the cement, but not an increase in the volume of cement and water.

If cement were a crystalline substance a certain definite volume would be assumed upon the taking up of the water of crystallization, which volume would be thereafter constant except for minute changes due principally to capillarity, as in the case of natural stones. Experiments and practical experience have abundantly shown, however, that cement and cement mortar are not volume constant, but that they invariably shrink upon setting and hardening in air and expand upon setting and hardening in water; phenomena that are not characteristic of crystalline substances.

Many experiments have shown that the coarser particles of cement constitute simply so much inert matter. It is known that even the sieve having 300 meshes per lineal inch is not fine enough to pass only active material, which latter can be separated out only by some suspension method which retains only the finest impalpable powder or " flour."

Experiments made by Messrs. H. S. Spackman and R. W. Leslie strongly support the above statements. Cement that had passed the 200-mesh sieve was separated into three parts by shaking it in kerosene and allowing it to settle. The portion which settled in less than thirty seconds was only slightly acted upon by water after even two years. The portion which settled in from thirty seconds to one minute was only acted upon by water in from three to four months, and was hydrated only in part then. The portion which remained in suspension more than one minute was acted upon immediately, swelling up and forming a very voluminous jelly.

Still other evidence might be cited in support of the theory that the setting of cement is due to the formation of a colloidal mass by the addition of water to the finest portion of the ground clinker which, as the only active part of the cement, binds together the coarser inert particles of clinker as a sort of " mineral glue," which has little strength or hardness in itself, but has great binding power, which is more or less cumulative in its action when formed in contact with inert matter such as the coarser particles of clinker or with sand. The " colloidal theory " has gained wide recognition and much support in the last few years.

Really intelligent scientific study of the problem of the hydration of Portland cement has become possible only since the determination of the constitution of cement has been made by the Geophysical Laboratory. Such a study has recently (1914) been completed by Messrs. A. A. Klein, petrographer, and A. J. Phillips, former assistant chemist, of the Pittsburgh Laboratory of the U. S. Bureau of Standards.*

Hydration experiments were made upon the following compounds which had been found to be constituents of cement by the Geophysical Laboratory:

Monocalcium aluminate (CaO, Al_2O_3).
Monocalcium silicate (CaO, SiO_2).
5 : 3 calcium aluminate ($5CaO, 3Al_2O_3$).
Beta orthosilicate ($2CaO, SiO_2$).
Tricalcium aluminate ($3CaO, Al_2O_3$).
Gamma orthosilicate ($2CaO, SiO_2$).
Tricalcium silicate ($3CaO, SiO_2$).

Limes burned at different temperatures, and ground to various degrees of fineness were also experimented upon, and the following commercial cements—a high silica cement, a low silica cement, a high iron cement, and a high magnesia cement.

The tests consisted of (1) hydration on microscopic slides with water without access of air, (2) hydration with superheated steam in a cylinder, (3) hydration in an autoclave, and (4) molding with limited quantities of water, approximating those used in normal consistency mixes. Lime-water and plaster of Paris solution were also used as hydrating mediums. Petrographic methods were employed to determine the hydration processes and final products.

Tricalcium aluminate hydrated with restricted amounts of water formed amorphous hydrated tricalcium aluminate very quickly, this amorphous form slowly changing to the crystalline form. With a large excess of water crystalline hydrated tricalcium aluminate was formed.

"Monocalcium aluminate and 5 : 3 calcium aluminate split off amorphous hydrated alumina and form the crystalline hydrated tricalcium aluminate."

The hydration of the aluminates in lime-water revealed no new products, but in plaster solution the additional compound tricalcium sulpho-aluminate, $3CaO, Al_2O_3, 3CaSO_4, xH_2O$, was observed. This

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* The following discussion of the problem of cement hydration is based upon an as yet unpublished abstract of the report which will later be published by the Government. This abstract has been privately communicated to the author by Mr. P. H. Bates of the Bureau of Standards.

compound is crystalline in form and identical for all three aluminates. Its formation is only incidental in the retardation of the initial set caused by gypsum. The high temperature and pressure of the autoclave destroys it.

"Burned lime hydrates with an excess of water to either the crystalline or amorphous form of lime hydrate. A preponderance of the former is produced where the lime is coarse and high burned, while the formation of the amorphous form is favored by fine grinding and low burning.

"The monocalcium silicate and the gamma orthosilicate do not hydrate, while the beta form of the latter hydrates but slightly with water after long periods. Lime-water and plaster solution do not materially increase hydration, whereas a solution of the calcium aluminate gives the maximum hydration and best-appearing test pieces. The twenty-eight-day test pieces of beta orthosilicate and the aluminates, while exhibiting fairly good rigidity, have by no means the strength of corresponding neat cement briquettes. The aluminates are completely hydrated, but the beta orthosilicate shows only a comparatively slight hydration. The hydration product of the silicate is amorphous hydrated orthosilicate, there being no lime hydrate split off and no needles of hydrated monocalcium silicate formed, as noted by others.

"The tricalcium silicate hydrates readily and quickly with all concentrations of water, the products of hydration being crystallized lime and amorphous hydrated orthosilicate. Molded specimens set hard in five hours and show no disintegration after twenty-eight days in water. It has no favorable effect on the hydration of beta orthosilicate. Mixtures of it and the aluminates show first the beginning of hydration of the aluminates followed shortly by the hydration of the silicate. Molded specimens of these are dense, hard, and strong, comparing very favorably with neat cement briquettes.

"On the hydration of cement, the first constituent to react is the aluminate, with the formation of amorphous hydrated tricalcium aluminate, with or without amorphous hydrated alumina. The sulphoaluminate crystals are also formed and the low-burned or finely ground lime hydrates. This occurs within a few hours after the cement is gauged. The next compound to hydrate is the tricalcium silicate. This commences within twenty-four hours and is generally completely hydrated within seven days. Between seven and twenty-eight days, the amorphous aluminate commences to crystallize and the beta orthosilicate, the least reactive compound, begins to hydrate. The twenty-four-hour strengths are due mainly to the hydration of the aluminates and of any fine-grained, low-burned lime present. The large increase in strength between twenty-four hours and seven days is due mainly to the tricalcium silicate hydration. The increase between seven and twenty-eight days is due to the hydration of the beta orthosilicate. Where there is a decrease in strength during this period it is due to the hydration of very high-burned free lime as in very high-burned, high-limed cements, or to the crystallization of the aluminates, as in high-alumina cements. The iron compounds in a cement are resistive to hydration. It does not form crystalline hydration products, but occurs as a rust-like material.

" The initial set of cement is affected by the action of small amounts of electrolytes in retarding coagulation of the aluminate material. With a limited amount of water, such as used in normal consistency mixes, the aluminates coagulate and separate from supersaturated solutions as amorphous bodies, the rate of coagulation being affected by such small quantities of electrolyte as to nullify the possibility of the reaction being solely a chemical one.

" Failure of cement in accelerated tests is due to the growth of large lime hydrate crystals. The disrupting action results from the pressure caused by growing crystals. Cements will fail in the boiling test which contain lime sufficiently fine and high burned, so that during boiling it hydrates and crystallizes. The growth of crystals is sufficient to cause disintegration. When a cement passes the boiling test but not the autoclave test, it contains lime so coarse or high burned as not to hydrate in the boiling test, but only in the autoclave, due to the high temperature and pressure employed. Some cements will pass either test only after aging. In this case aëration with insufficient water to allow solution and crystallization causes the lime to hydrate as amorphous hydrate, and in the accelerated tests there is no crystallization and no disintegration.

" The reactions when cement is subjected to the autoclave test are not abnormal. The disintegration action attributed to the crystallization of the sulpho-aluminate has been exaggerated."

(Note that the arguments of Michaelis in support of the " colloidal theory " of setting and hardening do not conflict in any way with the explanation of the phenomena above given. Note also that the authors above quoted carefully avoid the use of the inexact term " colloid," which is so often used by Michaelis.)

SPECIFIC GRAVITY

108. Significance. Until lately the significance of the specific gravity of a cement was considered to be its usefulness " in detecting adulteration and under-burning." More recently, investigations have conclusively shown that the principal factor influencing specific gravity is the degree of seasoning of cement; that specific gravity tests will not detect under-burning; and that tests will only detect adulteration in the case of a few classes of adulterants, and even then only when the adulteration is very considerable. Its importance may, therefore, be considered only very limited.

109. Specification and Results of Tests.* "The specific gravity of the cement thoroughly dried at 100° C. shall not be less than 3.10. Should the test of cement as received fall below this requirement a second test may be made upon a sample ignited at a low red heat. The loss in weight of the ignited cement shall not exceed 4 per cent."

Experiments made at six different mills by members of the Association of American Cement Manufacturers gave an average of 3.14 for the specific gravity of the under-burned cements, and 3.18 for that of the hard-burned ones. Few freshly made American Portlands will be found outside these limits except under special circumstances as indicated in the discussion that follows:

110. Influence of Thoroughness of Burning on Specific Gravity. Until a few years ago, as above noted, the specific gravity of a cement was considered a valuable indication of under-burning. Experiments have shown, however, in every instance that the specific gravity of under-burned cements is only very slightly below that of normally burned cement and still, in the main, well within the specified limit. Experiments made by Meade † upon clinker with varying degrees of burning gave the following results:

1. Very soft under-burned clinker	3.208
2. Slightly under-burned clinker	3.222
3. Normally-burned clinker	3.214
4. Very hard-burned clinker	3.234

These values all appear very high in consequence of the fact that the clinker was ground and tested as quickly as possible after burning, thus preventing the usual lowering in specific gravity by the absorption of carbon dioxide and water from the air.

111. Influence of Adulteration on Specific Gravity. The substances most readily available and practicable for adulteration of Portland cements in this country are natural cements, limestones, clay, slaked lime, slag, sand, and natural volcanic tufa.

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* Specifications for cement herein cited are, unless otherwise noted, those of the American Society for Testing Materials adopted Aug. 16, 1909.

† Meade, "Portland Cement," p. 380.

Natural cements will of course lower the specific gravity of the blend in direct proportion to the specific gravity of the natural cement used. Assuming an average natural cement to have a specific gravity of 2.95, and an average Portland 3.15, it will appear that a blend would have to contain about 25 per cent natural cement before the specification would bar its use.

Cement rock and limestones having specific gravities in the neighborhood of 2.7 and 2.8 could not possibly be used without detection in percentages exceeding 10 to 15 per cent. Clay or slaked lime would similarly be detected if used in more than very small amounts. Slag, having a specific gravity of about 3.0, can be used in very large amounts without detection through excessive lowering of the specific gravity of the blend. Sand and volcanic tufa have, so far as we are aware, never been used except when the fact of the product being a blend is not concealed. The former, being more expensive to manufacture than pure Portland, must be able to show properties better than pure Portland in order to find a market. The latter has only been made use of to our knowledge in the plant operated by the city of Los Angeles in connection with the construction of the Los Angeles aqueduct.

The specific gravity of an ignited sample of cement is invariably higher than that of the original sample, so that the retest provided for in the second clause of the specification will give no indication regarding adulteration. The loss on ignition will serve to detect the presence of an adulterant only in the event of adulteration by addition of raw materials after calcination, the ignition loss of the other adulterants being in themselves low.

112. Influence of Seasoning on Specific Gravity. It is a well-recognized fact that the absorption of carbon dioxide and water from the air, which begins as soon as the clinker leaves the kiln and continues as the clinker is ground and the cement stored, results in a material lowering of the specific gravity of cement. This process results in the formation of calcium carbonate, whose specific gravity is 2.70, and calcium hydroxide with a specific gravity of 2.08. If, for example, 2 per cent of water is absorbed, the specific gravity might be lowered from 3.125 to about 3.06, and if a like percentage of CO_2 were absorbed, the specific gravity might be lowered from 3.125 to about 2.92. Meade [*] quotes the following tests, which show plainly the effect of seasoning upon specific gravity of cement. It will be noted that in each case the loss due to seasoning is regained upon ignition.

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[*] Meade, loc. cit., p. 382.

EFFECT OF SEASONING UPON SPECIFIC GRAVITY OF CEMENT

Sample No.	1		2		3		4		5		Ave.	
Condition.	Dried at 100°.	Not Dried.	Dried at 100°.	Not Dried.	Dried at 100°	Not Dried.	Dried at 100°.	Not Dried.	Dried at 100°.	Not Dried.	Dried at 100°.	Not Dried.
Freshly made	3.19		3.21		3.16		3.15		3.20		3.182	
After 28 days	3.16	3.11	3.18	3.12	3.14	3.10	3.12	3.09	3.14	3.08	3.148	3.100
After 6 months	3.13	3.08	3.09	3.04	3.12	3.08	3.09	3.03	3.09	3.04	3.104	3.054
Ignited	3.18		3.21		3.18		3.15		3.19		3.182	
After 6 months												

113. Summary and Conclusions. Low specific gravity may be caused by adulteration in large amounts; it is not indicative of under-burning; it is indicative of the degree of seasoning. Since seasoning is in general considered desirable for all Portland cements and absolutely necessary for some, it is not advisable to reject any cement upon the basis of failure to come up to the specified value of specific gravity unless the history of the cement and its manufacture is known.

Fineness of Grinding

114. Significance. As above noted, the fact that the coarser particles in cement constitute so much inert matter has long been recognized. Acceptance of the explanation by the Bureau of Standards of setting and hardening gives the importance of extremely fine grinding an entirely new significance. In general, " the more finely cement is pulverized, all other conditions being the same, the more sand it will carry and produce a mortar of a given strength."

No other one detail in the manufacture of Portland cement has so great an influence upon all the properties of the product, and it seems reasonable to expect that the future improvement of Portland cement will be largely dependent upon the perfection of pulverizing machinery that will without excessive cost produce a cement having a maximum amount of extremely fine impalpable particles.

115. Specification and Results of Tests. "It shall leave by weight a residue of not more than 8 per cent on the No. 100, and not more than 25 per cent on the No. 200 sieve." Recent improvements in pulverizing machinery have made a great improvement in the fineness of commercial cements, and most of those now marketed in this country will leave a residue not exceeding 2 to 5 per cent on the No. 100, and 10 to 15 or 20 per cent on the No. 200 sieve.

A great need is felt for the adoption of some standard method of determining the proportion of extremely fine particles or flour in cement. Many methods of separation by suspension in a liquid or in air have been brought out, but none has been standardized and each gives results not in accord with those of another method. It is impossible at this time, therefore, to determine except in a general way the effect of the proportion of material finer than the No. 200 sieve upon the properties of cement, or the actual proportions of material of a given size under the No. 200 sieve in commercial cements.*

116. Influence upon Soundness. It has usually been considered that increased fine grinding is operative in improving the soundness of a cement. The extent of the improvement is slight, however, and not such as to justify extremely fine grinding for the sake of improved soundness alone. Meade cites experiments which show that in some cases an unsound cement is made sound by grinding to an impalpable powder; in the majority of cases, however, soundness was attained only by seasoning following fine grinding, making it appear that the beneficial effect of fine grinding is only indirect, in that it affords additional opportunity for seasoning.

117. Influence upon Setting Time. In general, increased fineness of grinding has the effect of making a cement more quick setting. It appears that high-alumina—and consequently low-lime—cements have their setting time most affected by fine grinding, so that in general the higher a cement is in lime, the more finely it may be ground without reducing the setting time to too great an extent.

Extremely fine grinding, or separation of the cement so that the flour is obtained, produces a cement whose set is almost instantaneous. These facts are exactly in accordance with the conclusion above quoted from the report of the Bureau of Standards upon the hydration of cement.

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* A method of determining the proportion of extremely fine particles in cement has recently been developed at the U. S. Bureau of Standards, and is now undergoing standardization (1914).

Fig. 67, which is based upon data given by Meade,* illustrates well the effect of increased fineness upon the setting time. This curve averages the results obtained in tests of eight different cements, each being ground to six different degrees of fineness.

118. Influence upon Neat and Mortar Strength. Many experiments have shown conclusively that increased fine grinding of cement is not only not beneficial to neat strength, but even lowers the neat strength. On the other hand the sand-carrying capacity and mortar strength of a cement is very considerably increased by finer grinding.

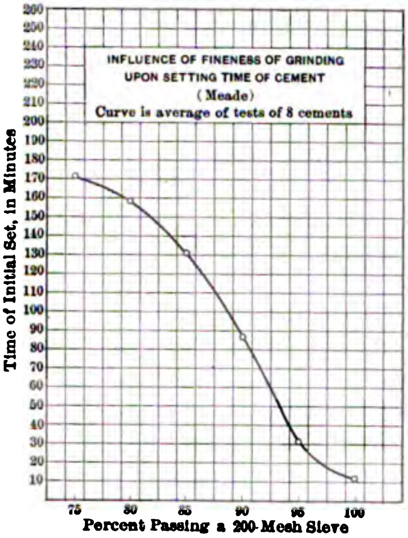

FIG. 67.

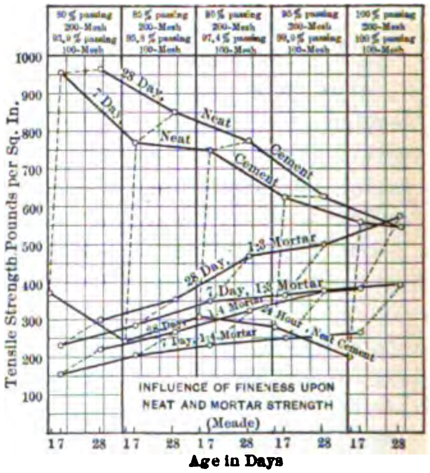

FIG. 68.

These facts again are entirely in accord with the Bureau of Standards' explanation of setting and hardening.

Amorphous hydrates have little mechanical strength in themselves, and the more finely a cement is ground the more nearly will the active particles constitute the entire mass of the cement to the exclusion of coarser inert matter. The amorphous hydrates have, however, a great binding power, and will form a strong mass if inert particles are present to be cemented together. These inert particles may either be the coarser portion of the clinker, or sand added in a mortar. In either case the greater the actual amount of impalpable powder present, the greater the quantity of inert matter that may be added and still produce a cement or mortar of a given strength.

* Meade, loc. cit., p. 399.

Fig. 68 shows admirably the effect of differing degrees of the fine grinding of the same cement, upon the neat and the mortar strength.*

119. Summary and Conclusions. The maximum degree of fineness compatible with reasonable manufacturing costs is desirable. The strength except in neat tests is greatly increased and the sand-carrying capacity and mortar strength very materially increased by increased fineness of grinding; the time of setting is materially shortened, but this effect may be lessened and injury in this repsect prevented by making the cement as high in lime as is possible without endangering soundness by the presence of excess free lime.

Time of Setting

120. Significance. The rapidity with which a cement sets is simply a criterion by which the suitability of a cement for use under given conditions may be established. Absolutely no analogy can be traced between the rapidity with which a cement sets and the strength it will ultimately develop. A cement to be used in submarine construction, for instance, should be quick setting, while a cement to be used under circumstances where rapid handling and deposition in the forms without delay is impossible, should be slow setting.

121. Specification and Results of Tests. "It shall develop initial set in not less than thirty minutes, and must develop hard set in not less than one hour, nor more than ten hours."

So many factors influence the time of setting, such as temperature, amount of water used in gauging, presence of sulphates, etc., that no general statement may be made as to the rate of setting of Portland cements.

122. Influence of Temperature. In general, the higher the temperature the shorter the setting time will be.

The diagram of Fig. 69, taken from Tetmajer's "Communications," Vol. 6, shows this effect very markedly. Many other series of tests, more recently made than Tetmajer's, agree very well with the older tests, and the latter are quoted here because they are more comprehensive than most later tests. (It should be noted that the cement used by Tetmajer was rather slower setting than the normal.)

123. Influence of the Percentage of Water Used to Gauge the Cement. The percentage of water used to gauge cement influences its setting time to a very marked degree, a wet mix setting much more slowly than a dry mix. It is on this account that tests of setting time are always made with a paste possessing a standard degree of plasticity (i.e., a normal consist-

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* Meade, loc. cit., p. 401.

ancy mix). Fig. 70, plotted from tests quoted by Meade, shows the characteristic effect of variations in the amount of water used in gauging upon the time of setting. The degree of humidity of the air similarly affects the setting time and, for the sake of uniformity in testing, the determination should always be made in a moist closet.

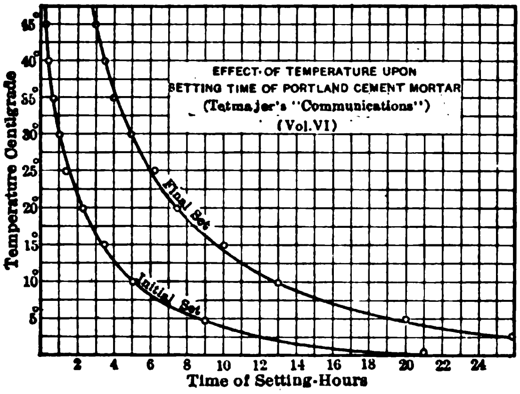

Fig. 69.

124. Influence of Sulphates. As noted in a previous chapter in discussing the manufacture of Portland cement, the addition of lime sulphate to the clinker before grinding is absolutely necessary in order to retard the set sufficiently to pass the requirements of commercial use. The addition of plaster of Paris or gypsum up to 1½ to 3 per cent retards the set, and further additions beyond this point of maximum retardation has the opposite effect.

125. Influence of Seasoning. The effect of seasoning upon the setting time of cement is the source of considerable difficulty for the cement manufacturer. Freshly made cement which is found to be slow setting is frequently found after a few weeks' seasoning to have become quick setting. Conversely, some cements, originally quick setting, become slow setting after seasoning. The latter case is usually less serious than the former, as the cement will probably still be suitable for marketing. In the case of the cement which becomes quick setting upon storage the cause of the difficulty is apt to lie in the composition of the cement and may usually be remedied by increasing the lime content.

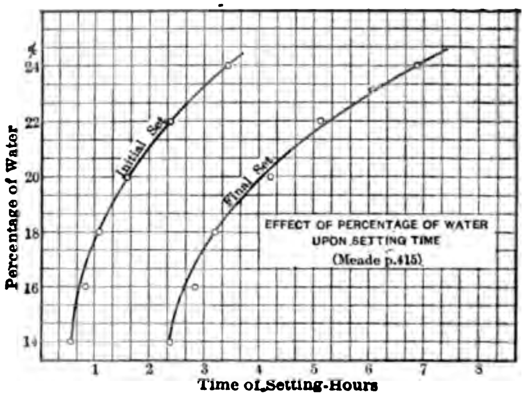

Fig. 70.

126. Summary and Conclusions. The time of set is often an important consideration in the choice of a cement for a particular purpose, and on account of the effect of storage upon the setting time the test should preferably be made after delivery of the cement on the work. The effect of temperature and the percentage of water used in mixing as well as the humidity of the air, is so marked that the determination of the setting time must always be made with extreme care under standardized conditions.

SOUNDNESS

127. Significance. Soundness in a cement implies the absence of those qualities which tend to destroy the strength and durability of a cement. The importance of soundness is second to that of no other property of cement. If a cement is ultimately unable to withstand the disintegrating influence of the medium, air or water, in which it is placed, the development of a high degree of strength at the ages usually tested means less than nothing.

Unsoundness is manifested by a lack of constancy of volume, disintegration being caused almost entirely by expansion occurring after the cement has set and acquired a certain degree of inelasticity.

Since any amorphous hydrate shrinks during drying and expands when wetted, it is evident that this behavior on the part of the amorphous hydrated constituents of gauged cements must cause shrinkage of neat cement in air and expansion in water. These changes in volume are very much lessened by mixing with inert material as in sand mortar, the degree of volume change being dependent upon the richness of the mortar. The consequence of the desiccation of the cement is the appearance of fine hair-cracks on the surface of cement or rich mortar used as a plaster or top coat. These fine hair-cracks should not be taken to be an indication of defective cement, but their appearance simply is an indication of the use of too rich a mixture. The subject of the expansion and contraction of cement and mortar from the above causes will be discussed further hereinafter.

Unsoundness, as the term is commonly used, is not caused by the phenomena above discussed, but is due to disruptive action caused by crystallization of certain of its constituents, pressure being exerted by growing crystals. The principal constituent so involved is the lime present in the free state.

The presence of free lime in the cement may be due to an excess of lime in the composition of the cement; failure to calcine at a temperature sufficient to combine all the lime present with the silica and alumina; or failure to grind the raw materials sufficiently fine and mix sufficiently well for the lime to enter combination. If this lime were simply present in its usual condition as an amorphous substance it could never be held responsible for the phenomena exhibited by an unsound cement, because it would become hydrated immediately upon contact with the gauging water and its expansion would be harmless because it would have taken place before setting had begun. Two explanations have been advanced to account for the slowness with which hydration does take place: one theory supposes that the free amorphous lime particles become coated with clinker and are so protected and hydration delayed; the other theory is based upon the fact discovered by Day, Shepherd, and Wright in the researches conducted at the Geophysical Laboratory, that loose powdered lime, if kept for any length of time at 1400° C., agglomerates to form crystals which grow rapidly. These finely powdered crystals when mixed with water appear at first to be inert, but after a time the hydration takes place with explosive violence. Both theories appear to have some verification in the observed behavior of unsound cement, and it is probable that both free amorphous lime and free crystalline lime are present.

The presence of excess dehydrated magnesia may less frequently be the cause of unsoundness. In this event unsoundness will be observed only after a much longer period, since magnesia which has been highly heated remains inert for a long time before undergoing hydration. A long series of experiments following the discovery that the cement involved in several disastrous failures of structures in Europe were very highly magnesian, proved that the addition to cement of highly calcined magnesia produced enormous expansion, while light calcined magnesia was without influence on soundness because of the rapidity with which it became hydrated. In recognition of the effect of strongly calcined magnesia upon the soundness of cement the standard specifications of all countries limit the amount of magnesia, the English to 3 per cent, the United States to 4 per cent, and the German to 5 per cent.

The presence of excess sulphates is also thought to be the cause of unsoundness in some few cases. The expansion is not due in this case to the hydration of lime sulphate, but is attributed to the formation of calcium-sulpho-aluminate, which is dangerous only in large quantities. The standard specifications of England limit the SO_3 to 2.75 per cent, the German to 2.5 per cent, and the United States to 1.75 per cent.

128. Specification. " Pats of neat cement about 3 inches in diameter, ½ inch thick at the center, and tapering to a thin edge, shall be kept in moist air for a period of twenty-four hours.

" (*a*) A pat is then kept in air at a normal temperature and observed at intervals for at least twenty-eight days.

"(*b*) Another pat is kept in water maintained as near 70° F. as practicable, and observed at intervals for at least twenty-eight days.

"(*c*) A third pat is exposed in any convenient way in an atmosphere of steam, above boiling water, in a loosely closed vessel for five hours.

"These pats to satisfactorily pass the requirements shall remain firm and hard, and show no signs of distortion, checking, cracking, or disintegrating."

129. Influence of Seasoning. Since, as above noted, unsoundness is primarily due to presence of free lime, either amorphus or crystalline, in cement, exposure to the air will in time produce soundness by the conversion of the lime into carbonate of lime or lime hydrate through the agency of the carbon dioxide and moisture always present in the air. Meade quotes tests made on several samples of cement originally unsound, rendered sound by simple aëration in paper bags in the laboratory. Several cements which checked more or less badly when tested freshly ground, became sound upon seasoning from one day to two weeks. One which partly disintegrated when tested freshly ground, became sound after twenty-eight days' aëration, and another which entirely disintegrated when first tested, became sound after ninety days' aëration.

130. Influence of Fineness. As noted above, free amorphous lime may probably be so coated with clinker as to be protected from aëration to a large extent, and similarly protected from the water used in gauging for some time, with resultant ultimate unsoundness if such particles of clinker-coated lime are not broken up by fine grinding. Increased fine grinding therefore will often promote soundness in a cement that will not season sound without fine grinding, but the fine grinding should probably be regarded as beneficial only indirectly, in that it makes possible more complete aëration.

131. Effect of Sulphates. The primary effect of sulphates added to cements is greatly to delay the time of setting. Their addition in small percentages does result in appreciable improvement in soundness, as determined in the steam test, but it is probable that here again the effect is only indirectly due to the sulphates, the set being delayed by the latter till the free lime has become hydrated with no resultant evidence of unsoundness. This view is strengthened by the fact that many cements which successfully pass the steam test fail in the air test. The possible effect of excess sulphates prejudicial to soundness has been discussed above.

132. Summary and Conclusions. Soundness is the one most essential property of cement. Its absence is manifested by cracking and disintegration after cement has set, due to the disruptive force caused principally by the expansion of certain of its constituents, notably free lime, upon becoming hydrated in the crystalline form. Soundness is promoted by thorough seasoning, by fine grinding of the raw material and the clinker, by keeping the magnesia content low, and by not exceeding the content of sulphates necessary to retard the set sufficiently.

TENSILE STRENGTH

133. Significance. The tensile strength of cement is in itself of very little importance, because cements are rarely depended upon to withstand tensile stresses. The significance of tensile strength as revealed by laboratory tests is therefore limited entirely to the degree of accuracy in the assumption that there exists a fixed relation between tensile strength and compressive strength, soundness, and other properties which contribute to the satisfactoriness with which it meets the demands put upon it as a material of construction. The assumption is also often made that the tensile strength of neat cement bears a more or less close relation to the strength of mortars under the same character of stress.

It will be shown that a relation between tensile strength and compressive strength can be established, but that it is by no means a constant relation at all ages, and that it also varies greatly with different cements, and with different mixtures; that there is absolutely no ground for concluding that a high tensile test of cement at the usual age of testing indicates soundness; often, in fact, it affords ground for the opposite conclusion; and that the neat tensile strength is no indication of the strength of the cement in mortars and concrete.

In view of the above considerations there remains but one defense of the use of tensile strength test results as a criterion of suitability—the fact that tensile tests are easily made with inexpensive equipment, as compared with the requirements for compressive strength tests. Even this consideration does not justify the dependence that is commonly placed upon the neat tensile strength, since the infinitely more important mortar tests, involving the determination of the power of the cement to adhere to the surfaces of foreign particles, may be made with equal facility. The latest specifications of the American Society of Civil Engineers * include specifications for the making of compressive strength tests. The tensile strength test has been included, however, both for neat cement and mortar mixtures. The new German specifications adopted by the Association of German Portland Cement Manufacturers, March, 1910, have abandoned the neat tests altogether, and have substituted com-

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* "Final Report of the Special Committee on Tests of Cement." Transactions, Am. Soc. C.E., Vol. 75, p. 665, Dec., 1912.

pressive tests for tensile tests, except that the making of tensile mortar tests on the work is provided for if required for the sake of expediency, no reliance being placed upon these field tests, however, in case of dispute.

134. Specification and Results of Tests. Neat Cement. "The minimum requirements for tensile strength for briquettes 1 inch square in cross-section shall be as follows, and the cement shall show no retrogression in strength within the periods specified:"

Age.	Strength.
24 hrs. in most air	175 pounds
7 days (24 hrs. in moist air, 6 days in water)	500 pounds
28 days (24 hrs. in moist air, 27 days in water)	600 pounds

Tests of tensile strength are dependent upon a great many factors which influence the accuracy of the results. Perhaps the greatest of these is the personal equation, which plays an important part in every operation in making tests of tensile strength. In addition to the disturbing personal factor, tensile strength is greatly influenced by the amount and the temperature of gauging water, the method of mixing and molding in general, the temperature and humidity of the air, the form of briquette, the design of the testing machine and the grips, and the manner of storage of the briquettes prior to testing. All of these factors have to do with testing operations. The actual tensile strength, the conditions of testing being considered constant, is dependent primarily upon the composition of the cement, particularly the content of bases, alumina, and iron oxide; secondarily, upon the temperature of burning, and the fineness of grinding. Fig. 71 shows the average tensile strength, neat, of seven representative brands of Portland cement tested at the Structural Materials Laboratory in St. Louis,* 1905–07.

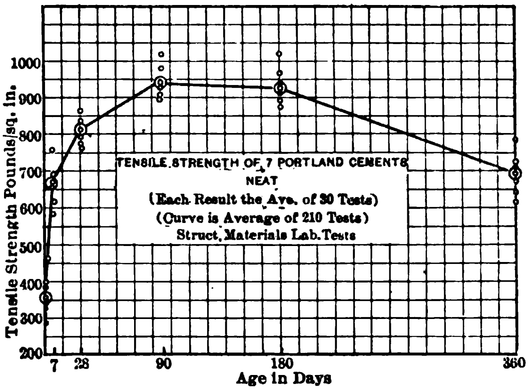

FIG. 71.

135. Influence of Lime Proportion on Tensile Strength. An increase in the proportion of lime yields a stronger cement until a point is passed

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* Bulletin 331, U. S. Geol. Survey.

beyond which further additions mean the presence of excess free lime with consequent unsoundness. Cement prepared in the modern rotary kiln is capable of holding a rather larger proportion of lime with safety than that made by the older processes where neither so high nor so uniformly distributed temperatures were attainable. High-limed cements which are still perfectly sound are slow setting, but attain their maximum strength early, sometimes showing retrogression in tensile strength after as short a period as seven days and usually showing retrogression after longer periods.

This retrogression is not noted, however, in compression tests, and it appears possible that the low tensile test results are due to the brittleness of such cements and the difficulties in the way of so griping the briquettes as to make the stress a pure tensile stress.

136. Influence of Temperature of Burning on Tensile Strength. The temperature of burning affects the tensile strength chiefly indirectly, in that the temperature of burning must be high for high-limed cements and therefore high for cements of high tensile strength. Under-burning will result in weak cement, but over-burning probably has no injurious effects so far as the quality of the product is concerned, though it means a lack of economy in kiln fuel and extra expense in grinding.

137. Influence of Fineness of Grinding upon Tensile Strength. This question has been discussed above under the head of " Fineness,—Influence upon strength and sand-carrying capacity," where it is shown that, owing to the amorphous hydrate formation in gauging and the nature of these hydrates, increased fine grinding is not beneficial to neat tensile strength, but materially improves the strength of mortars in that the additional opportunity for cementing action afforded by fine grinding greatly increases the cohesive power of a cement.

TENSILE STRENGTH OF SAND-CEMENT MORTARS

138. Significance. The remarks made above regarding the significance of tensile tests of neat cement largely cover the subject of tensile tests of mortars. If tensile tests of cements must be depended upon, the briquettes should at least be mortar briquettes, since in the neat tests one of the most important properties of cement, the ability to adhere to the surfaces of foreign particles and masses, is not determined. The remarks made above concerning tensile vs. compressive tests of neat cement apply equally well to the consideration of mortars, as do also the remarks concerning the factors influencing the results of tensile tests, and the discussion of the influence of the lime ratio, temperature of burning, and fineness of grinding upon tensile strength.

139. Specification. "The minimum requirements for tensile strength for briquettes 1 inch square in cross-section shall be as follows, and the cement shall show no retrogression in strength within the periods specified."

ONE PART CEMENT, THREE PARTS STANDARD OTTAWA SAND

Age.	Strength.
7 days (1 day in moist air, 6 days in water).............	200 pounds
28 days (1 day in moist air, 27 days in water).............	275 pounds

140. Standard Sand. The following specification has been adopted (February, 1912) by the American Society of Civil Engineers. Its provisions are, however, practically identical with the standard specification in force since 1904, when the use of crushed quartz was abandoned.

"The sand to be used should be natural sand from Ottawa, Ill., screened to pass a No. 20 sieve and retained on a No. 30 sieve. The sieves should be at least 8 inches in diameter; the wire cloth should be of brass wire and should conform to the following requirements:

No. of Sieve.	Diameter of Wire. Inch.	Meshes per Linear Inch.	
		Warp.	Woof.
20	0.016 to 0.017	19.5 to 20.5	19 to 21
30	0.011 to 0.012	29.5 to 30.5	28.5 to 31.5

"Sand which has passed the No. 20 sieve is standard when not more than 5 grams passes the No. 30 sieve in one minute of continuous sifting of a 500-gram sample."

The average tensile strength in 1 : 3 standard mortar of the same seven brands of cement whose average neat strength was noted in Art. 134 and Fig. 71, is shown by the curve of Fig. 72, which has been plotted from data obtained at the Structural Materials Laboratory in St. Louis.

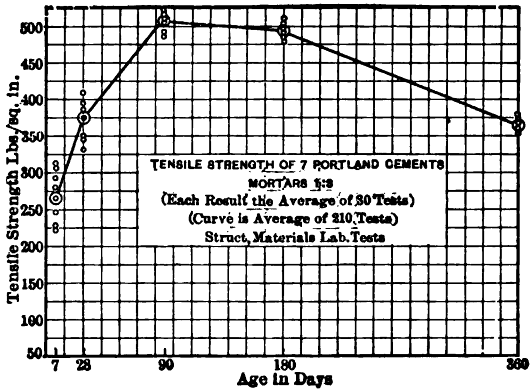

FIG. 72.

141. Effect of Fineness of Sand upon Mortar Strength. The size and granulometric composition of a sand is well known to have a marked influence upon the strength of mortars. It will later be shown that the strength of mortars is directly proportional to the density for a mortar of given volumetric composition. The relation between fineness of sand and tensile strength of mortars is excellently shown in Figs. 73, 74 and 75, which are plotted from tests made on 1 : 1, 1 : 2, and 1 : 3 mortars in the laboratories of the College of Civil Engineering, Cornell University, by Dr. R. P. Davis.*

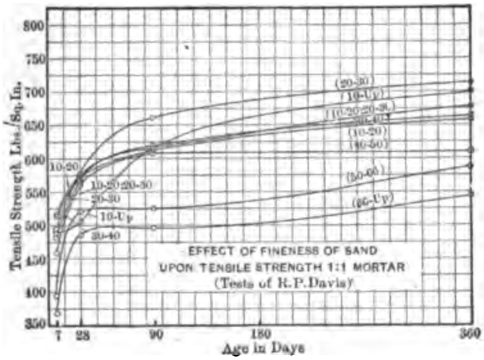

FIG. 73.

For these tests a beach sand was used, composed of nearly pure quartz with slight traces of mica. The various sizes of sand experimented with were synthetically prepared from the natural sizes of the above-mentioned sand. Mortars were made of fifteen different granulometric compositions, but to avoid confusion on the curve sheets the results obtained with the three natural sizes and some of the blends of equal amounts of various sizes have not been included on the curve sheets.

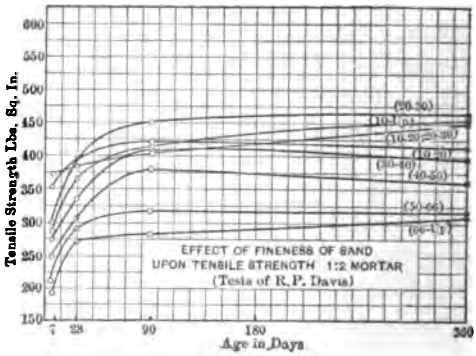

FIG. 74.

It will be noted that for the three mortars tested the results are remarkably alike. In every case the sand between the No. 20 and No. 30 sieves gave a mortar of maximum strength at all ages except the short-time tests and the three-months' test in the case of the 1 : 3 mortar. The sand of all sizes finer than that passing the No. 10 sieve ranked second except for the short-time tests, and exceeded the 20 to 30 sand at three months in the 1 : 3 mortar. The blend of equal amounts of 10 to 20 and 20 to 30 sand ranked third and (except for the 1 : 1 mortar where the 30 to 40 sand

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* Dr. R. P. Davis, "Cornell Civil Engineer," Vol. 19, pp. 114–124, Jan., 1911.

excelled it) the 10 to 20 sand ranked forth. All of the finer sizes of sand ranked lower in the order of their fineness.

142. Relation between Density of Mortars and Tensile Strength. The series of tests above quoted affords important support to the theory generally held that the tensile strength of a mortar of given volumetric composition is proportional to the density of the mortar. Figs. 76 and 77 show the fairly constant relation between density and mortar strength at all ages for 1 : 2 and 1 : 3 mortars, established by Davis' tests. Fig. 78 shows the relation between density and average mortar strength at the four periods tested for 1 : 1, 1 : 2, and 1 : 3 mortars.

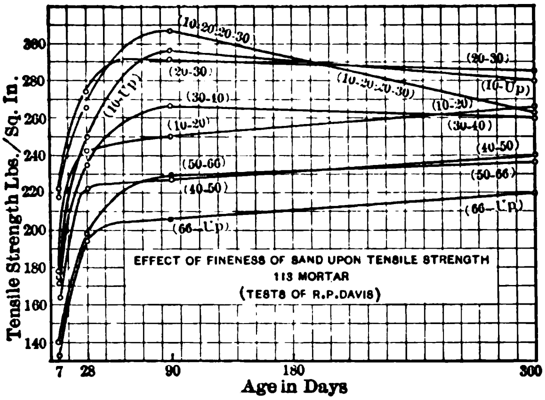

FIG. 75.

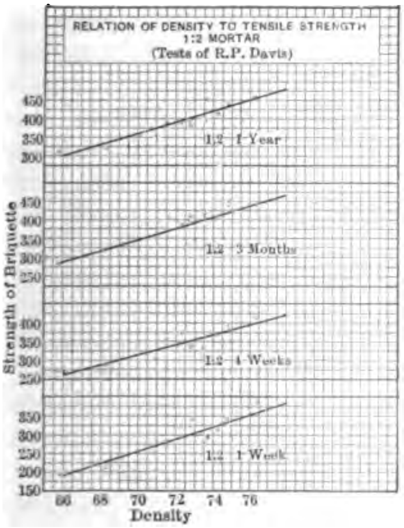

FIG. 76.

143. Influence of Mica in Sand upon Tensile Strength of Mortars. Davis in the above-mentioned articles quotes tests made by Mr. W. N. Willis * showing the detrimental effect of the presence of even small percentages of mica added to 1 : 3 mortars made with standard Ottawa sand. This information is presented by the curves of Fig. 79.

"This loss of strength, which is very considerable even if there is only a slight amount of mica present, averaging about 25 per cent with only 2½ per cent of mica, is due to two causes: first, because of its irregular shape the percentage of voids is very large, and second, on account of its smooth surface good bonding will not obtain."

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* W. N. Willis, "Engineering News," Vol. 49, p. 145.

144. Influence of Cleanliness of Sand upon Strength. Sand used for structural purposes is never really clean unless washed on the work, and the importance of this factor is only just coming to be fully recognized in concrete construction. The character of the impurities in sand is more important than the amount. If largely vegetable loam, the danger is in direct proportion to the amount of organic matter in the loam or silt. Experiments made by Mr. Sanford E. Thompson * led to the conclusion that to be injurious the organic matter must constitute over 10 per cent of the silt and at the same time over 0.1 per cent of the sand.

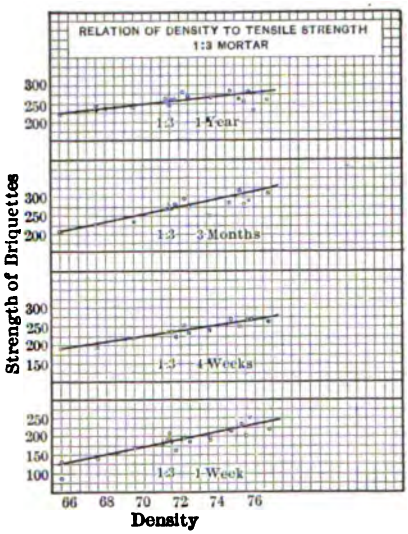

FIG. 77.

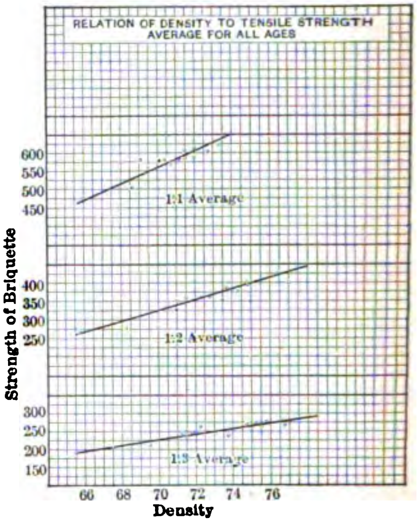

FIG. 78.

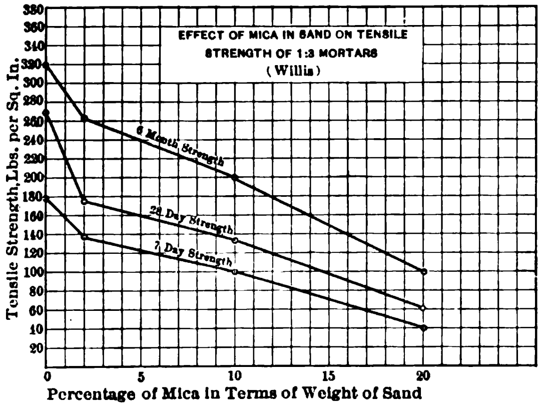

FIG. 79.

If the impurities in sand are not of a vegetable loam nature, they are of a mineral character, as clay. The effect of clay is dependent entirely

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* Sanford E. Thompson, Trans. Am. Soc. C.E., Vol. 65.

upon its state of subdivision and the uniformity with which it is distributed through the sand. The effect is probably not purely physical, but due rather to the distinctly colloidal properties of the clay. In most laboratory tests the addition of clay has been found beneficial to strength, or harmless up to a certain limit. This limit has usually been found to be from 5 to 10 per cent of the sand, the beneficial effect not being very marked, however.

The above results attained in laboratory tests should not be taken to indicate that similar percentages of clay will be beneficial or harmless in naturally clayey sands used in practice for concrete or mortars. The manner of distribution and degree of fineness of the clay will be the determining factors, and the amount permissible will in general not approach the above limits.

145. Effect of Addition of Hydrated Lime to Cement and Mortars. The addition of hydrated lime in small percentages to cement and mortars usually has a very appreciable effect upon the resultant tensile strength shown by tests. The curves of Fig. 80 well illustrate the injurious effect in the case of neat cement and the slightly beneficial effect, in amounts up to 15 per cent, in the case of 1 : 3 mortar using standard Ottawa sand. These curves are based upon tests made by Mr. Harry Gardner.*

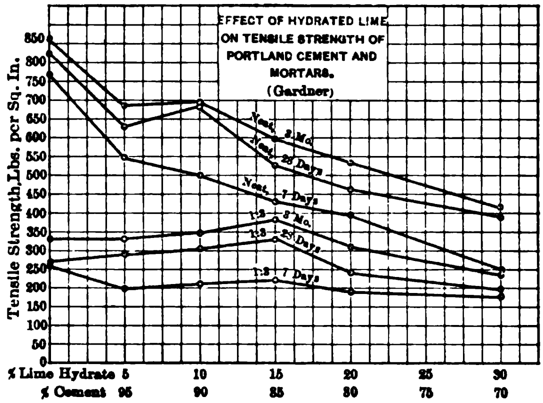

Fig. 80.

Investigations of the effect of additions of lime hydrate upon the strength of cement mortars have not invariably shown that additional mortar strength is attained by so doing. Tests made by Mr. H. S. Spackman † indicate that the addition or substitution of 10 per cent of hydrated lime has no marked effect upon either the tensile or compressive strength of mortars.

The idea has been advanced by Mr. Spackman that the addition of the hydrate has a beneficial effect on the strength of mortars mixed and used on the work, which is not exhibited by laboratory tests. The hydrate

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* Harry Gardner, Eng. Rec., Vol. 64, p. 309.

† H. S. Spackman, "Concrete Cement Age," Vol. 4, p. 112.

does not by chemical combination affect the process of hardening and gaining strength, but its use is alone justified by the mechanical work it performs during the few moments between gauging and final placing in the work—the period of mixing and handling the mixture. The addition of hydrate makes a fat, viscous mortar in which the sand and cement will not separate to as great an extent as they will when Portland cement is used with sand alone. This tends toward the production of a mixture of greater uniformity and with less voids, therefore securing a mortar of more uniform strength. Under the ideal conditions of mixing and molding in the laboratory this mechanical advantage would not be noted.

Aside from the effect of hydrated lime additions upon the strength of cement mortars, the practice of making such additions is often justified by the advantage derived from the standpoint of permeability. Hydrated lime is an excellent waterproofing substance for incorporation in mortars and concrete. Such additions also produce mortar and concrete which show less expansion and contraction with alternate increase and decrease of moisture content.

146. Relation between Tensile and Compressive Strength. The existence of a more or less definite and constant relation between the tensile strength and the compressive strength of cement has been often asserted, and the truth of the assertion widely accepted. In fact such a relation is the only basis of justification of the adoption of tensile strength as a criterion of the suitability of a material for use in situations where it will be subjected only to compressive stress.

In order to study the question and make a comparison between the results obtained with representative modern American Portland cements, tested in accordance with the present standards of testing, and the older studies based upon tests with European cements made twenty years ago by the methods then in vogue, the tests made in the Structural Materials Laboratory at St. Louis, Mo., in 1905–1907 * have been selected as the most comprehensive series to tests recently made.

Seven prominent representative brands of American Portland cement were selected for these tests, and the manner of testing was in accord with the present standard methods (1914). Each brand of cement was tested in tension and in compression at ages up to one year, ten tests of each kind being made for each age with each cement, both neat and in standard 1 : 3 mortar. The tension tests were made with standard 1-inch square briquettes in a semi-automatic briquette-testing machine, and the compressive tests were made upon 2-inch cubes in hand-operated screw-testing machines. The sand used in the mortars was standard

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* Bulletin 331, U. S. Geol. Survey.

Ottawa sand. From the data tabulated in the report above mentioned the curves shown in Figs. 81 and 82 have been plotted.

A study of these curves shows that while the average curve representing the ratio of compressive to tensile strength for the 210 tests of the seven brands is a smooth curve, showing a rapid increase in the ratio up to twenty-eight days, and a fairly uniform increase between twenty-eight days and one year for both neat and 1 : 3 mixtures, the individual brands depart widely from the average. At seven and twenty-eight days this individual departure from the average amounts to about 12 per cent each way for neat cement. Individual brands among the 1 : 3 mortars depart from the average ratio almost 40 per cent at twenty-eight days, and 15 to 20 per cent at one year.

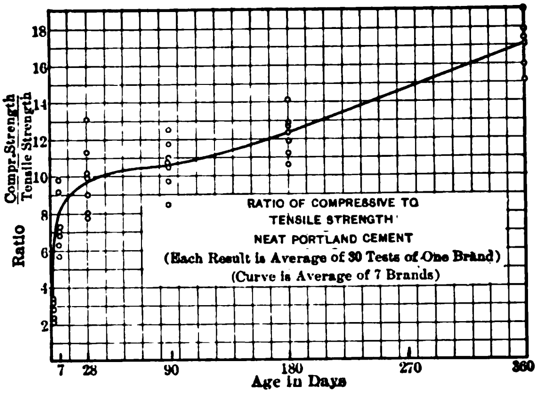

FIG. 81.

Comparing the curve for neat cement with the curve for 1 : 3 mortar we find that the ratio is very different in the two cases, the ratio for neat cement having a value at any period about 1.8 times that found in the case of the 1 : 3 standard mortars at the corresponding period.

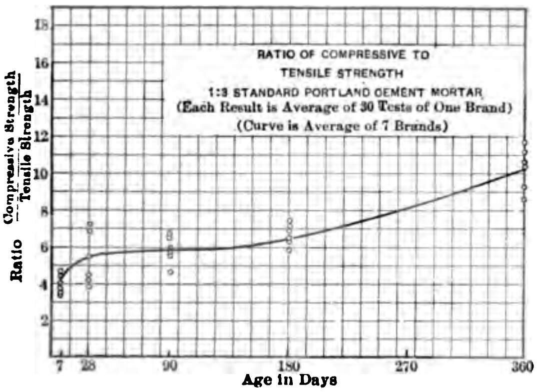

FIG. 82.

It appears therefore that tensile strength of neat cement mixtures are not comparable with compressive strength upon the same basis with 1 : 3 mortars.

A similar series of tests made with a blend of the above seven brands of cements and twenty-two different natural sands was also made at the Structural Materials Laboratory and reported in the above-mentioned paper. The tabulated data there presented have been summarized, and the ratios of compressive to tensile strength plotted in Figs. 83 and 84. In Fig. 83 each result is the average of thirty tests, the curve therefore representing the mean of 240 tests of each kind. Fig. 84 represents the values obtained in 1 : 3 mortar mixtures of the above blend of seven cements with twenty-two different sands.

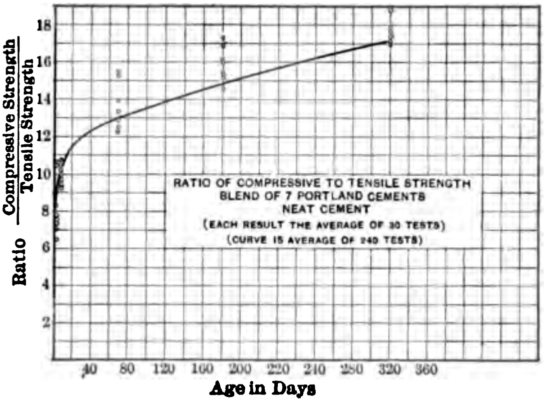

Fig. 83.

Since the results for each sand, if individually plotted, would cause confusion on the diagram, only the average for all the mortars, the average for the five mortars showing the highest value of the ratio, and the average for the five mortars showing the lowest value of the ratio are plotted.

The value of the ratio found for individual mortars in many cases far exceeded the departure of the high- and low-average curves from the average curve for all the mortars.

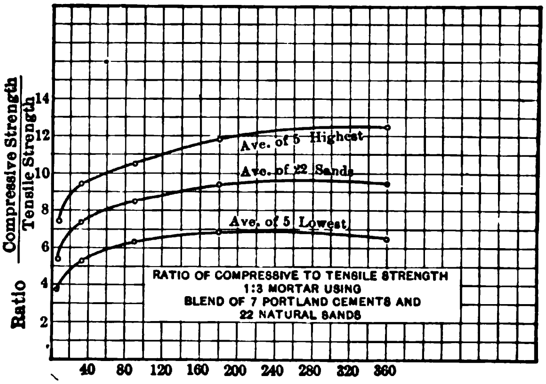

Fig. 84.

The curves of Figs. 83 and 84 are here introduced simply to further support the opinion that the ratio of compressive to tensile strength of cement mixtures, neat and mortar, is dependent upon so many factors that the tensile strength cannot in general be taken to be more than a very approximate indication of the probable compressive strength of the same cement and even then the age, the mixture, the sand used in mortars, etc., are factors which must be carefully taken account of.

147. Tensile Strength and Soundness. The fallacy of the belief, often held, that a cement which shows up well in the early neat tests of tensile strength is not apt to fail to meet satisfactorily the conditions of structural use, through lack of constancy of volume, is well illustrated by Fig. 85, which is based upon tests made by Mr. W. P. Taylor.* These curves are derived from over two hundred nearly consecutive tests of a single brand of Portland cement, one hundred of them failing in the soundness test, and one hundred passing.

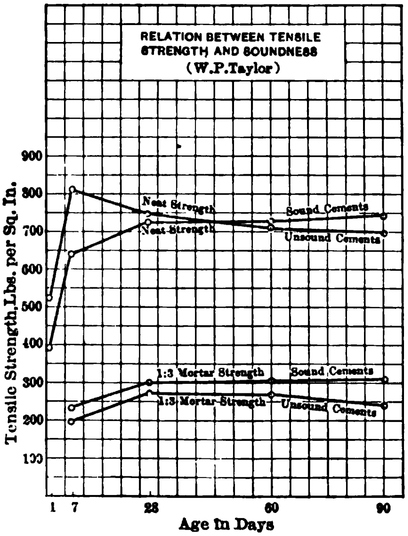

FIG. 85.

It will be noted that the early strength of the neat tests of those samples failing to pass the test is much the greater, while the opposite is true in the case of the mortar samples. These data therefore afford an additional bit of evidence to show that mortar tests should be preferred to neat cement tests.

148. Relation between Neat and Mortar Strength. The relation between neat strength and standard 1 : 3 mortar strength in both tension and compression is shown by Figs. 86 and 87, which are based upon the series of tests quoted above in discussing tensile vs. compressive strength.

It has been stated above that the mortar strength or sand-carrying capacity of a cement is dependent largely upon the proportion of extremely fine particles in a cement. It is therefore not surprising to find that in the series of tests of seven Portland cements from which the curves of Figs. 86 and 87 are plotted, no definite relation can be established between neat and 1 : 3 standard mortar strength. The seven cements probably varied greatly in the percentage of flour present, although the facts could not be discovered by the ordinary sieve tests which were made.

Only two general conclusions may be based upon the curves of Figs. 86 and 87: first, that the ratio of neat to 1 : 3 mortar strength in compression is about 1 : 8 times as large as the ratio of neat to 1 : 3 mortar strength in tension, and second, that the value of this ratio in both

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* W. P. Taylor, Trans. Am. Soc. for Test. Matrls., Vol. 3, 1903.

compression and tension rapidly decreases for about three months, after which no pronounced further decrease is observed.

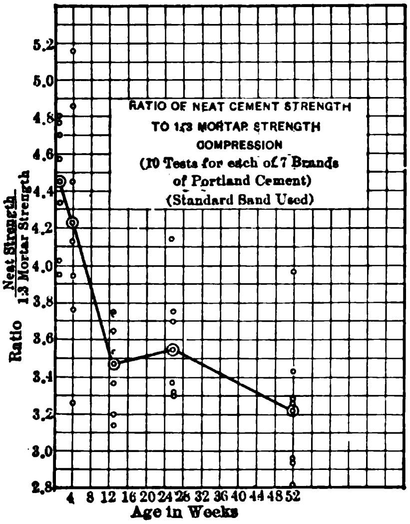

FIG. 86.

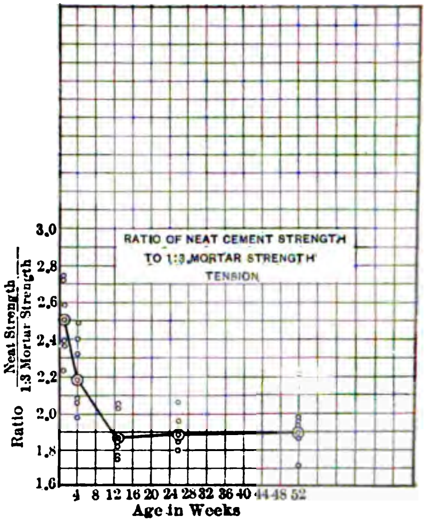

FIG. 87.

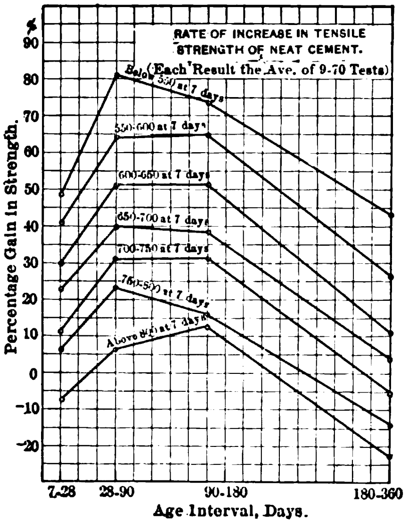

FIG. 88.

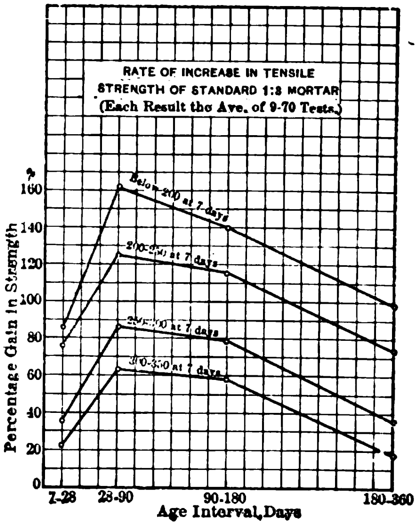

FIG. 89.

149. Rate of Increase in Tensile Strength and Loss of Strength Observed in Long-time Tests. Figs. 88 and 89 represent the rate of increase in tensile strength, in neat and standard 1 : 3 mortar mixtures, for the seven representative American Portland cements used in the Structural Materials Laboratory series of tests above mentioned. It will be noted that for these typical cements the rate of gain in tensile strength at all ages is approximately inversely proportional to the strength at seven days, those cements which show the lowest tensile strength at seven days maintaining the best rate of gain in strength at all ages.

Figs. 90 and 91 bring out the same facts in connection with the rate of gain in compressive strength of the same cements. Specifications which require given percentages of increase in strength between the seven-day and the twenty-eight day period seem therefore to be justified, provided the specific percentage gain required is made to depend upon the strength shown at seven days.

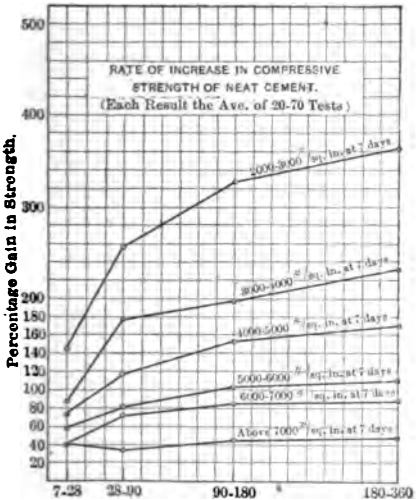

FIG. 90.

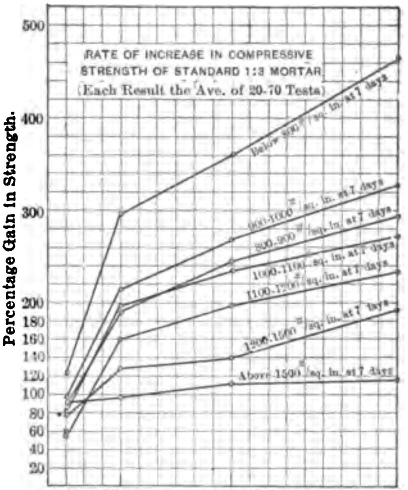

FIG. 91.

High strength values at the early ages have often been asserted to be indicative of probable retrogression in strength at ages of six months and upwards. The extent to which this view is supported by the structural Materials Laboratory Tests is indicated by the following table, which has been compiled from the data given in Bulletin 331 of the Geological Survey.

It will be noted that, while a majority of the cements show retrogression between the ages of 90 and 180 days, and all of them between the ages of 180 and 360 days, few, however, show retrogression at ages under 3 months, and then only in the cases of the cements showing extremely high strength at 7 days.

RETROGRESSION IN TENSILE STRENGTH OF CEMENT, NEAT AND STANDARD 1 : 3 MORTAR

(Tests of Structural Material Laboratory)

(237 tests made at each age, 7 brands of cements)

Mixture.	Strength at 7 days.	Per cent Showing Retrogression between ages of (days)			
		7 and 28.	28 and 90.	90 and 180.	180 and 360.
Neat	Below 550	0	0	67	100
	550–600	0	0	47	100
	600–650	0	0	36	100
	650–700	0	10	62	100
	700–750	0	6	44	100
	750–800	32	0	67	100
	Above 800	67	0	33	100
1 : 3	Below 200	0	0	86	86
	200–250	0	0	62	71
	250–300	0	0	48	100
	300–350	0	0	57	100

The standard 1 : 3 mortars behaved as did the neat cement except that there were no instances of retrogression at ages under three months.

In contrast to the behavior of cements and mortars in tension, the following table shows the behavior of the same cements and mortars

RETROGRESSION IN COMPRESSIVE STRENGTH OF CEMENT, NEAT AND STANDARD 1 : 3 MORTAR

(Tests of Structural Materials Laboratory)

(237 tests at each age, 7 brands of cement)

Mixture.	Strength at 7 days.	Per cent showing Retrogression between ages of (days).			
		7 and 28.	28 and 90.	90 and 180.	180 and 360.
Neat	2000–3000	0	0	0	25
	3000–4000	0	0	12	25
	4000–5000	0	12	12	24
	5000–6000	0	7	0	40
	6000–7000	0	7	14	29
	Above 7000	0	60	20	60
1 : 3	Below 800	0	0	0	20
	800– 900	0	0	0	14
	900–1000	0	0	8	25
	1000–1100	0	0	0	12
	1100–1200	0	0	0	20
	1200–1500	0	0	22	0
	Above 1500	0	40	40	20

in compression. It will be noted that, with the exception of a few samples which tested extremely high at seven days, only a small proportion of the neat cement showed any retrogression under six months and the percentage showing retrogression between six months and one year is hardly a third of the like percentage for tensile tests.

When we examine the behavior of the 1 : 3 mortars in compression we find that the percentage showing retrogression is practically negligible at all ages with the exception of a few mortars of extremely high early strength.

150. Summary, Tensile Strength. Tensile strength has little significance as a criterion of the suitability of a cement for use as a structural material. The mortar tests should always be given greater weight than tests of neat strength, and compressive tests should always be made the criterion of mechanical strength where the conditions of use permit.

Tensile strength is increased with increased lime content in the cement (below the limit imposed by the danger of unsoundness); temperature or burning, so long as the clinker is not under-burned, affects tensile strength only in that high-limed cements require high-kiln temperatures; extremely fine grinding is beneficial to mortar strength but not to neat tensile strength.

Mortars are stronger if the sand be comparatively coarse, that between the No. 20 and No. 30 sieve showing the highest tensile strength; mortars of greatest density show highest tensile strength; mica in sands is injurious to mortar strength even though it does not exceed 2.5 per cent; uncleanliness in a sand is dangerous in proportion to the amount of organic matter present, as little as 0.1 per cent having been found notably injurious; clay, if finely divided and uniformly distributed, has been found usually beneficial in laboratory tests, in percentages not exceeding 5 to 10 per cent; in practice the permissible amount in a sand may be much lower.

Hydrated lime in small percentages decreases neat strength but may increase mortar strength slightly.

The ratio of compressive to tensile strength is dependent upon too many factors to make the latter a safe indication of the probable value of the former; high tensile strength is no indication of soundness, unsound cements often showing high early strength in neat mixtures, though not in mortars; the ratio of neat to 1 : 3 standard mortar strength is very variable, depending on the percentage of flour in the cement; it is about 1.8 times as large in compression as it is in tension at all ages and rapidly decreases with age until an age of three months or more is reached; the rate of increase in tensile or compressive strength is dependent upon the early strength values, a low-testing early-strength cement showing a high rate of increase at all ages, and vice versa; retrogression in neat and also mortar tensile strength at six months is quite general, and a one year practically universally characteristic of Portland cements; in compression, on the other hand, retrogression is rare even with neat mixtures, and 1 : 3 mortars the probability of its occurrence may be considered almost negligible.

COMPRESSIVE STRENGTH

151. Significance. Compressive strength has already been stated to be the best criterion by which to judge the suitability of a cement for use in construction. The conditions of testing more nearly approximate the conditions met with by the material in use than is the case in any other laboratory test of cement, and the results therefore should have the greatest weight in the selection of a cement or the determination of quality.

152. Specification and Results of Tests. There is, unfortunately, no standard specification, or even any widely accepted specification, in this country for compressive strength of cement, either neat or in mortar mixtures. The German standard specification is as follows:

" Slowly setting Portland cement shall show a compressive strength of at least 120 kilograms per square centimeter (1710 pounds per square inch) when tested with three parts by weight of standard sand, after seven days' hardening, one day in moist air and six days under water; after further hardening of twenty-one days in the air at room temperature (15° to 20° C.) the compressive strength shall be at least 250 kilograms per square centimeter (3570 pounds per square inch). In cases of controversies, only the test after twenty-eight days is decisive.

" Portland cement which is intended for use under water shall show a compressive strength of at least 200 kilograms per square centimeter (2850 pounds per square inch) after twenty-eight days' hardening, one day in moist air and twenty-seven days in water."

Figs. 92 and 93 show the compressive strength of the same seven representative brands of cement, the tests of which were used to illustrate the typical values of tensile strength above.

The discussion above under the head of tensile strength has for the most part a direct application in the consideration of compressive strength. Particularly does the above discussion of neat vs. mortar tests apply with equal force to compressive tests.

The rate of increase in compressive strength, and retrogression in strength, have been considered above under these heads, in the discussion of tensile strength.

153. Modulus of Elasticity of Cement and Mortars. The modulus of elasticity of cement and mortars has seldom been determined, and no comprehensive series of tests is available. It has been shown, however, that the modulus is not a constant for a given specimen, but decreases rapidly with increased load. In general the modulus is found to be lower as the mixture becomes leaner, and for a given mixture increases with age. Fig. 94 gives values of the modulus determined by tests made at the age of three months for a single brand of cement in several mixtures. The values here given are slightly higher than the average cements and mortars show at this age.

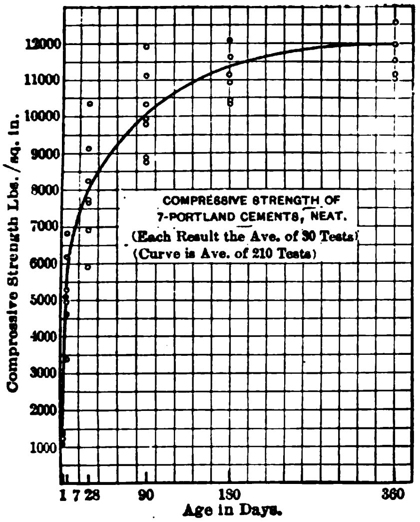

FIG. 92.

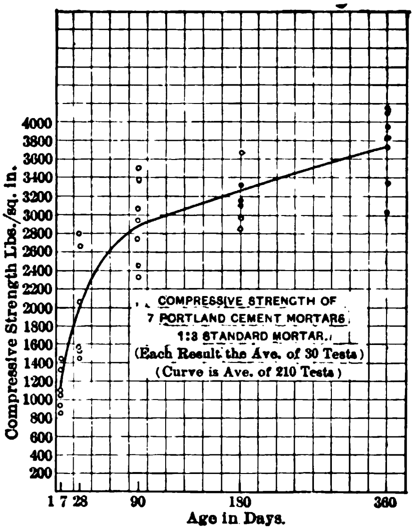

FIG. 93.

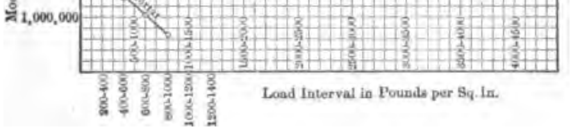

FIG. 94.

154. Shearing Strength of Cement and Mortars. The shearing strength of mortar is important not only because of the intimate relation between shearing strength and compressive strength, but because of the fact that mortars and concretes are often subjected to shearing stress when used structurally. Very few tests of shearing strength have been made, however, probably largely because of the difficulty found in subjecting a specimen to a purely shearing stress.

The tests made by Bauschinger and published in the Proceedings of the Munich Technical Institute in 1879 still remain almost the only source of information in this important property of mortars.

The following table has been prepared from Bauschinger's report. The specimens used were prismatic in shape, the cross-section being 2.4 inches by 4.8 inches. The specimens were stored in water. Each result in the table is the average of nine tests. For comparative purposes the tensile and compressive strengths of the same mixtures are given in the table. All stresses are given in pounds per square inch.

SHEARING STRENGTH OF CEMENT AND MORTARS

Mix.	Tension.			Compression.			Shear.		
	7 day.	28 day.	2 yr.	7 day.	28 day.	2 yr.	7 day.	28 day.	2 yr.
Neat	224	294	292	1910	2490	4680	271	346	415
1 : 3	95	169	272	880	1040	3340	116	188	375
1 : 5	64	103	232	537	977	2960	77	131	364

It will be noted that in these tests the shearing strength, expressed as a percentage of the compressive strength, varies in the case of the neat cement from about 14.2 per cent at seven days to about 8.4 per cent at two years; in the 1 : 3 mortar it varies from about 13.2 per cent at seven days to about 11.2 per cent at two years; and in the 1 : 5 mortar it varies from 14.3 per cent at seven days to 12.3 per cent at two years.

The shearing strength will in general be dependent upon the same factors as the tensile and compressive strength. In particular, the fineness of grinding of the cement, and the character of the sand used in the mortar will be important factors.

The Adhesive Strength of Cement and Mortars

155. Adhesion to Steel. The adhesion of cement and mortar to steel is important in the consideration of reinforced concrete and in the consideration of the holding power of anchor bolts, etc., which are imbedded in cement or mortar, or are grouted in place in drilled holes. Few tests are available to show the adhesive power of cement and mortars on steel, though many tests have been made to determine the same property for concretes. The following data are quoted by Sabin * from tests made with an ordinary river sand.

Each figure is the average of from five to fifteen tests made when the mortar was one month old, the imbedded steel being plain round rods.

ADHESION OF CEMENT AND MORTAR TO IRON RODS

Mixture.	Neat.	1 : 2	1 : 3
Average adhesion, lbs. per sq. in. of contact...............	313	264	111

156. Adhesion to Brick. The adhesion of cement and mortar to brick is of importance in all brick masonry construction. The following table has been constructed from a series of tests made by Sabin.† In each case two bricks were cemented together flatwise with a ¼-inch mortar joint and pulled apart in tension after a given interval. The specimens were stored in damp sand after the first forty-eight hours, and tensile tests of the same mortar were made for purposes of comparison on briquettes stored in the same manner. The consistency of the mortars was rather more moist than a normal consistency, but was not equal to that of mortar as usually used in masonry construction.

ADHESION OF CEMENT AND MORTARS TO BUILDING BRICK

Adhesion or Cohesion.	Age. Months.	Tensile Strength, Pounds per Square Inch, of Mortars Containing Parts Sand to One Cement.				
		None.	½	1	2	3
Cohesion...........	1	632	596	589	409	270
Adhesion...........	1	48	42	24	20	11
Cohesion...........	3	676	728	694	423	325
Adhesion...........	3	64	52	41	24	12
Cohesion...........	6	723	764	679	524	374
Adhesion...........	6	50	56	39	20	14

It will be noted that in general there is a fairly close relation between tensile strength and adhesion at all ages, the ratio of adhesion to cohesion being about 8.6 for neat cement, 7.1 for 2 : 1 mortar, 5.2 for 1 : 1 mortar, 4.8 for 1 : 2, and 3.8 for 1 : 3, showing that the addition of sand decreases the adhesion to brick more rapidly than it does the cohesive strength. Tests made with mortars to which lime paste had been added showed that the addition of 10 per cent lime increased the adhesive strength 120 to

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* Sabin, "Cement and Concrete," p. 300.

† Loc. cit., p. 293.

140 per cent; 16.7 per cent lime, 130 to 160 per cent; 25 per cent lime. 110 to 120 per cent; and 50 per cent lime, 75 to 80 per cent. The addition of lime increased the ratio of adhesion to cohesion in all percentages, since only small percentages of lime are even moderately beneficial to tensile strength and large percentages are detrimental.

157. Adhesion of Mortar to Various Materials. The adhesion of mortars to various building materials is a matter of much importance in construction work, but it has been little investigated. Fig. 95 gives the results of tests made by Gen. Wheeler and reported in the "Report of Chief of Engineers," 1895.

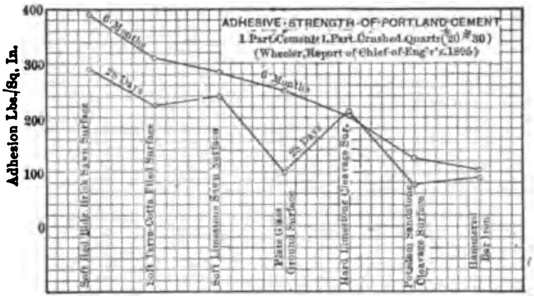

FIG. 95.

Discs of the material concerned were prepared, 1 inch by 1 inch square and $\frac{1}{4}$ inch thick, and inserted in the center of the briquette molds, which were subsequently filled with mortar and tested in the usual manner in tension.

158. Abrasive Resistance of Cement and Mortars. This property of cement and mortars is primarily of importance in the determination of the best mortar for use in the top coat of concrete floors, walks, and pavements. Resistance to abrasion will always be dependent not only upon the cement, as regards the tenacity with which it clings to the sand grains (which will be largely dependent upon its fineness and its lime content), but also upon the hardness of the sand used. Abrasion either wears away the cement and the sand particles or it pulls the sand grains out of the cement matrix.

With soft sand particles the resistance to abrasion with a given cement decreases constantly as the percentage of sand is increased. With hard sand grains the abrasive resistance increases as the proportion of sand increases, until the volume of cement becomes relatively too small to bind the sand grains together thoroughly. This limit is found to be reached when the mortar contains not more than two parts of sand to one of cement.

159. Permeability and Absorptive Properties of Cement Mortar. The permeability of mortar is a measure of the rate at which water under a given pressure will pass through a given thickness of the material. The absorptive properties of a mortar constitute a measure of the rate at which moisture will be absorbed when the mortar is exposed in damp situations or covered with water under negligibly small heads.

Permeability is an important consideration where watertightness of walls, etc., is required and percolation of water is not admissible.

Absorptive properties of a mortar determine its value as a dampproofing coat, particularly in the event of its use as a mortar over metal lath, which must be protected to prevent corrosion. In view of the disintegrating effect of expansion and contraction of mortars used as a plaster, etc., the moisture content (which largely affects this expansion and contraction) should not be greatly variable. Thus the least absorptive mortar will be most durable, up to the limit reached when the cement content is relatively so high that the expansion and contraction is disproportionately increased.

The determining of precise information concerning each of these properties is dependent upon a standardization of methods of conducting tests. Such standard methods have not yet been adopted, and it is therefore impossible to quote data as to the absolute permeability or absorptive power of mortars.

Tests to determine the relative permeability and absorptive power of mortars were made at the Structural Materials Laboratory at St. Louis in 1909, and are reported in Technologic Paper No. 3 of the Bureau of standards. Owing to the small number of tests made and certain unsatisfactory features of the testing method employed, only a few general conclusions will be drawn from the report of these tests.

(1) Permeability decreases rapidly for all mixtures with increase in age of the specimens when tested, (2) permeability decreases considerably with the continuation of the flow, (3) permeability increases with the leanness of the mixture, the dryness of the mixture, and increased coarseness of the sand.

Absorption was found to be dependent upon the same factors: it decreased with the age of the mortar as a rule, but not as rapidly as did the permeability (especially with the leaner mixtures); it decreased but slightly with increased richness of the mixtures; and the wetter mixtures were slightly less absorptive than the dryer mixtures.

160. The Expansion and Contraction of Cement Mortars. Changes of temperature are accompanied by changes in volume in cement mortars as in other structural materials. The temperature coefficient for mortars has been found with considerable accuracy to be 0.0000055, i.e., a specimen will suffer an increase or decrease in lineal dimensions of 0.00055 per cent for an increase or decrease of 1° F. (0.00099 per cent per degree centigrade).

Other volume changes due to the chemical processes of setting and hardening, and still others caused by variation in the moisture content of cement, constitute important considerations in the use of mortars and concrete. Professor A. H. White of the University of Michigan has made an excellent experimental study of this question, and his paper, entitled "Destruction of Cement Mortars and Concrete through Expansion and Contraction," read before the American Society for Testing Materials,* will be exclusively used in the present short discussion of the question.

Fig. 96 shows the average percentage of linear shrinkage of bars of neat cement kept constantly in air for periods up to four years, and also the average linear expansion of bars kept continuously in water for three years. Four different brands of Portland cement, all passing standard specifications for constancy of volume, were used.

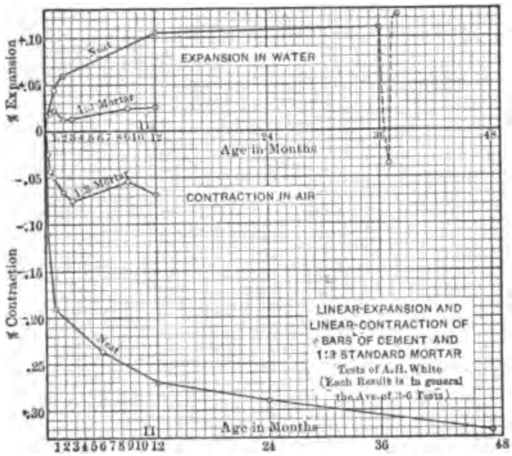

FIG. 96.

It is evident that in the case of neat cement fully one-half the total expansion or contraction comes in the first month, and there is very little change after one year. The expansion and contraction of 1 : 3 mortar was found to be very much less than that of neat cement, and in general, at the end of one year amounts to from one-quarter to one-third that of neat cement.

When bars of cement or mortar, after lying in water for three years, were allowed to dry in air at room temperatures, they gradually contracted till, at the end of two months, they had shrunk not only to their initial volume, but in most cases showed a considerable further contraction. When the bars so air-dried were again immersed in water they recovered in one day 90 per cent of the length they had lost in sixty-five days' air drying, and in most cases their length within one month exceeded that which they showed at three years, before having been air dried.

These percentages of expansion and contraction seem small, but

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* Proceedings, Am. Soc. for Test. Matrls., Vol. XI, 1911.

when closely examined appear to be far from negligible. The shrinkage of 0.322 per cent amounts to about 4 inches in 100 feet, and indicates clearly why neat cement cannot be used for interior floors or wall plasters, since if it did not crack, it would, when dry, have to withstand a ensile stress of 7500 pounds per square inch. In the case of such a plaster being constantly immersed and constrained from expanding, compressive stresses up to 5000 pounds per square inch would be encountered.

With 1 : 3 mortar instead of neat cement, the observed volume changes would, if expansion or contraction were restrained, mean the introduction of tensile or compressive stresses of 1250 pounds per square inch. Such stresses would in the case of the tensile stress caused by contraction necessarily mean failure by cracking.

CHAPTER VIII

CONCRETE

GENERAL

161. Concrete as a Structural Material. All of the masonry materials heretofore discussed—plasters, limes, and cements—have been strictly cementing materials. Alone, they are not used as masonry, but are used in combination with such non-cementing masonry materials as brick, stone, terra cotta, etc., or are used as a plaster coat in walls.

Concrete, considered as a cementing material, is unique in that it may be and commonly is used alone to form bulk masonry. If we consider the constituent materials from which concrete is made, however, instead of considering concrete masonry as one material, we find that we have to deal with a class of masonry which is made up of a large bulk of non-cementing materials bound together by a comparatively small amount of cementing material, just as is the case with stone or brick masonry. The distinction lies, however, in the fact that in concrete the non-cementing material is in a comparatively finely divided state, and is incorporated in a mix with the cementing material prior to placing on the work. In stone or brick masonry, on the other hand, the non-cementing material is brought upon the work in the shape of conveniently sized units with which the structure is built up, cementing material being used only as beds and joints to bind the stone or brick together.

One other distinction belongs to concrete alone among masonry materials—the fact that it may readily be strengthened or reinforced by the placing of steel therein. This makes possible its use in situations where tensile stresses are encountered, whereas stone and brick masonry may be depended upon to withstand compressive stresses alone.

The subject of reinforced concrete is so complex, the problems encountered in design and construction ones so peculiar to this class of construction alone, and the bibliography of the subject already so extensive, that the discussion of concrete in this chapter will not be made to include reinforced concrete.

CONCRETE MATERIALS

The Cement

162. Selection of Cement. Most engineers consider it a wise rule to use Portland cement for nearly all classes of concrete work. The conditions most favorable to the use of natural cement have been discussed above under the head of natural cement. Any cement used should be accepted under such standard specifications as those of the American Society for Testing Materials and, except on the least important work, samples from each shipment should be subjected to the standard tests recommended by the American Society of Civil Engineers.

163. Storage of Cement. After delivery on the work the cement should be carefully stored in weather-tight buildings the floor of which is raised from the ground. The storing should be done in such a manner as to permit of easy access for inspection and identification of each shipment.

164. Inspection and Testing. Each shipment of cement should be inspected by a competent inspector whose duty it is to select a sample for tests. The sample should be a fair average of a bag or barrel and, if conditions permit, about 1 barrel in every 10 should be sampled. Usually tests are made on a mixture of the individual samples, but in some cases on important work the individual samples are tested separately.

Sand for Concrete Aggregate

165. Granulometric Composition. In general, the discussion of sands for mortars included in Chapter VII (Arts. 141 to 144) applies with equal force to the consideration of sands for concrete. Investigations have abundantly shown that the sand should be for the most part coarse, rather than fine, that passing a 20-mesh sieve and retained on a 30-mesh sieve showing highest mortar strength. A sand showing a gradation in size from fairly coarse to fairly fine is preferable to either a uniformly coarse or a uniformly fine sand.

166. Shape of Sand Grains. It is usually specified that concrete sand shall be " sharp," by which is meant that the grains of sand shall be angular rather than rounded. For this reason, other things being equal, a bank sand is preferable to a river or beach sand. The advantage in favor of the former may be offset, however, in some instances by the greater cleanliness of the river or beach sand.

167. Foreign Matter in Sand. It has been shown in the chapter above referred to that the injurious effect of foreign matter in sand is dependent upon many factors. If the silt contains more than 10 per cent of organic matter, the latter constituting as much as one-tenth of 1 per cent of the sand, an appreciable injury results. Clay, if finely divided and uniformly distributed throughout the sand, appears to have little effect unless present in large percentages, perhaps 10 per cent or more. Mica is injurious even in very small percentages.

It is important, therefore, that the sand used on concrete work should be subjected to careful examination and tested no less systematically than is the cement. It is not sufficient to specify that the sand be " clean and sharp " and accept it upon the basis of a casual inspection made by taking a bit between the fingers to establish its grittiness, and determining its cleanliness by the amount of discoloration produced by rubbing it in the palm of the hand.

168. Voids in Sand. The proportion of voids in a sand determines the density of a mortar of a given cement-sand proportion and bears a similar relation to the density of a concrete made by the addition of larger aggregate to the mortar. The strength of mortar has been shown to be directly proportional to the density, which means, therefore, that a sand having the least void space will give a mortar and hence a concrete of greatest strength. This is simply corroboratory of the statement above made that a sand showing a fair gradation in size is in general preferable to one of uniform size.

Broken Stone or Gravel Aggregate

169. Gravel vs. Broken Stone. Either class of coarse aggregate may be perfectly satisfactory, and neither can be said to be wholly superior to the other. If the consistency of the concrete is such as to constitute a rather dry mix, more tamping is necessary to obtain a dense concrete with broken stone than is the case with gravel consisting of smoother and more rounded particles.

Gravel usually has a smaller percentage of voids than has broken stone, and therefore a compact concrete may be secured with a somewhat smaller amount of mortar than would be required for broken stone.

On the other hand, if properly tamped, the broken stone will to some extent interlock, forming a dense and strong concrete, the same effect being possible with a well-puddled wet mix. Also, the rough surface of the broken stone usually results in developing a greater adhesive strength or bond between the stone and the mortar. This latter consideration cannot be taken to be universally applicable, however, for the adhesion of cement to stone is not wholly a matter of roughness or smoothness.

170. Crushing and Screening Stone. Stone for concrete aggregate is crushed in exactly the same manner and with the same types of machines described in connection with the preparation of the rock for the manufacture of cement.

Stone or gravel should always be screened to remove all crusher dust and fine material, unless the material is of such a character that it may be considered as sand and due allowance for same made in fixing the proportions of the mixture.

171. Mechanical Analysis of Stone. On important work mechanical analysis of the aggregate is desirable since it affords a basis for determining the best proportions to be used with given materials, or for determining what sized material should be added to the aggregate to make it more satisfactory for use in a concrete of given proportions.

Mechanical analysis consists simply in passing the material through a succession of screens the mesh of which is of increasing fineness. The residue on each sieve is weighed and, beginning with the amount which has passed the finest sieve, the weights are successively added, so that each sum represents the weight of material which has passed a sieve of given mesh. These sums expressed as percentages of the total weight of material used are plotted as the ordinates to a curve the abscissae of which are the diameters of the particles. Fig. 97 represents the mechanical analysis of a rather typical gravel.

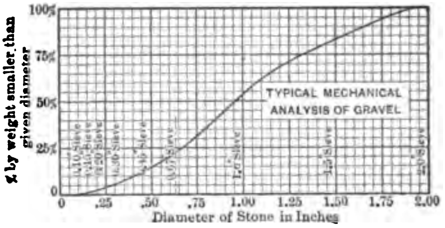

FIG. 97.

172. Size and Shape of Fragments of Stone. All material under $\frac{1}{4}$ inch or even $\frac{3}{8}$ inch should be removed from either crushed stone or gravel, this fine part being in some cases suitable for use as sand. The maximum size of coarse aggregate allowable depends upon the character of the work on which the concrete is used. Usually this limit is such a size as will pass a $2\frac{1}{2}$-inch ring. For massive concrete, however, the size may be such as will pass a 3-inch ring, and for reinforced concrete a size to pass a 1-inch, or even a $\frac{3}{4}$-inch ring, is required.

From the standpoint of minimum void space rounded stone are more desirable than irregular rough fragments; from the standpoint of ability to bond with the mortar they are deficient, however, so that in general the shape of the particles will be found to be much less important than the size and the hardness of the stone.

173. Voids in Stone or Gravel. As above noted, rounded particles of stone will have a smaller void space than will irregular broken fragments. The percentage of voids in natural gravel usually runs from about 30 to about 35 per cent, while in crushed stone the percentage will in general vary all the way from 30 to 45 per cent, depending upon the shape and gradation in size of the particles.

THE MAKING OF CONCRETE

PROPORTIONING CONCRETE *

174. Importance of Proper Proportioning. Upon important work, particularly if of large extent, a thorough study of the materials and the proper relative proportions will often effect better results with a saving in cost. The cement is always the most expensive ingredient, and therefore if it is possible, as it often is, to reduce the proportion of cement used by adjusting the proportions of the aggregates in such a manner as to produce a leaner mixture of equal or greater density and strength, economy is thereby effected.

175. Theory of Proper Proportioning. The theory of correct proportioning of concrete materials is based on one fact—namely, the greatest strength and imperviousness as well, is always obtained with a mixture of greatest density. The mortar will have a maximum density when there is just sufficient cement to fill the voids and coat the particles of the sand, and the concrete will have a maximum density when there is just sufficient mortar to fill the voids and coat the particles of stone.

Going a step farther, the concrete will be of maximum density with the least proportion of cement used, when each of the aggregates shows such a gradation in size as to make its void percentage least. That is, the proportion of particles of each successive size in each of the aggregates should be just sufficient to fill the voids in the next larger size.

176. Proportions in Practice. It is customary to state concrete proportions by volume, giving the number of parts of sand and stone to one of cement. It is hardly possible to state arbitrarily the proportions used in practice for concrete in any particular situation. The following division is given, however, as fairly representative of present conservative practice:

(*a*) 1 : 1½ : 3—a rich mixture used for columns and other structural parts subjected to high stresses or requiring especial water-tightness.

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* A very detailed discussion of concrete proportioning written by Mr. William B. Fuller will be found in Chapter XI of Taylor and Thompson's "Concrete, Plain and Reinforced."

(*b*) 1 : 2 : 4—a standard mixture used for reinforced floors, beams, columns, arches, engine and machine foundations where vibration occurs, sewers, conduits, etc.

(*c*) 1 : $2\frac{1}{2}$: 5—a medium mixture used for floors on the ground, ordinary machine foundations, retaining walls, abutments, piers, thin foundation walls, building walls, sidewalks, etc.

(*d*) 1 : 3 : 6—a lean mixture for massive concrete, heavy walls, large foundations under steady load, stone masonry backing or filling, etc.

(*e*) 1 : 4 : 8—a very lean mixture used only on unimportant work in very large masses.

177. Ingredients Required per Cubic Yard of Cement. Cement is usually bought and measured by the barrel, the weight of the barrel being 376 or 380 pounds net and the volume about 4 cubic feet. Sand and stone are bought and measured by the cubic yard, so that it will usually be convenient to determine the number of cubic yards of sand and stone or gravel for each barrel of cement in a concrete of a given mix.

The following rule will be found to be sufficiently accurate for the purpose of making preliminary estimates of quantities:

Let c = the number of parts of cement;
s = the number of parts of sand;
g = the number of parts of stone or gravel.

Then $\dfrac{10.3}{c+s+g} = P =$ barrels of cement per cubic yard concrete in place;

and $P \times s \times 4/27 =$ cubic yards of sand per cubic yard concrete;
$P \times g \times 4/27 =$ cubic yards of stone per cubic yard concrete.

This rule has been devised by experimental determination of the constant 10.3. It will give fairly accurate results with all classes of materials except with rather fine gravel, or stone which shows a very excellent gradation in size of fragments. In this event the quantities of each of the ingredients other than stone, as determined by the rule, will be found to be about 10 per cent in excess of actual requirements.

MIXING CONCRETE

178. Hand vs. Machine Mixing. Good concrete may be either hand or machine mixed, the choice depending largely upon the quantity required, and the consequent relative cost of the two methods. For all except the smallest work machine mixing will be less expensive than hand mixing, and for this reason, as well as the greater likelihood of obtaining uniformly well-mixed concrete of uniform consistency, machine mixing is generally preferred. Hand mixing is apt to be slighted because of the heavy labor demanded.

179. Method of Mixing by Hand. Hand mixing should be done upon a water-tight platform about 10 feet wide by 15 feet long. The measured quantity of sand having been spread over the surface of the mixing platform, the cement is spread evenly over the sand and the two mixed thoroughly dry, after which the required amount of water and stone may be added and the mass turned back and forth from one side of the board to the other until the mass is homogeneous in appearance and color. From three to five turnings are required to mix the concrete thoroughly.

FIG. 98*a*.—Cube Type Concrete Mixer.

180. Mixing Machines and Machine Mixing. Concrete-mixing machines are of two general classes—batch mixers and continuous mixers. In using the batch mixer, the materials are measured separately and charged into the machine in quantities sufficient to make a batch suited to the capacity of the machine. The required amount of water is added, and the mass is mixed and then completely discharged, after which the machine is recharged. In the continuous mixers the materials are delivered gradually to the machine, either already combined in the correct proportions or the rate of feed of each material may be regulated to produce the required mix as nearly as possible. Water is added as the materials pass slowly through the length of the mixer and the mass is discharged continuously from the lower end. Continuous mixers do not generally produce a concrete so thoroughly mixed or of as uniform a consistency as is obtained with the use of batch mixers. Specifications for important work very often stipulate that batch mixers be used.

Most concrete mixers consist of a rotating chamber into which the materials are charged and mixed with a complicated motion, due either to the shape of the mixer chamber or to the action of baffle plates placed on the inside walls of the mixing chamber. The cube mixer (Figs. 98*a* and 98*b*), requires no baffle plates because of its peculiar shape and manner of mounting. The drum-shaped mixer (Figs. 99*a* and 99*b*), and the duo cone-shaped mixer (Figs. 100 and 101), have baffle plates. The former is discharged by inclining the pivoted spout downward and outward while the machine continues to revolve. The latter is discharged by revolving the entire mixer on its trunnions.

FIG. 98*b*.—Cube Type Concrete Mixer.

DEPOSITION OF CONCRETE

181. Timber Forms. The investment in materials and the cost of labor in placing and removing forms often represents from 15 to 30 per cent of the total cost of concrete work. It is evident, therefore, that the correct design and construction of forms is a very important feature of the work. Forms must be substantially built, so thoroughly braced and wired that the finished concrete shall conform to the designed dimensions and contours, and made tight to prevent the leakage of cement-charged water.

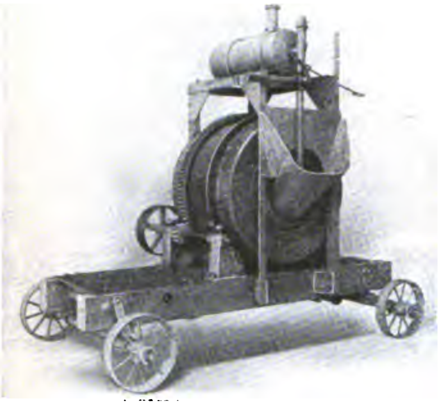

FIG. 99a.—Drum Type Concrete Mixer.

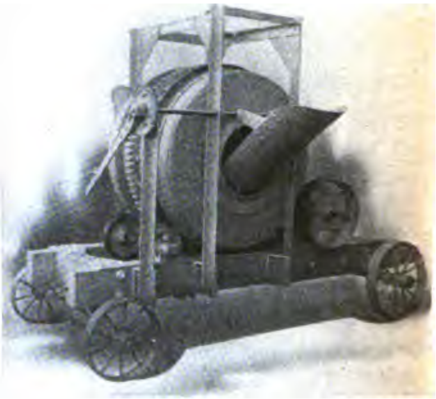

FIG. 99b.—Drum Type Concrete Mixer.

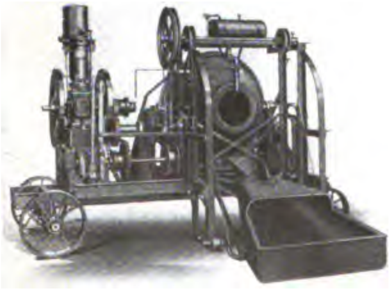

FIG. 100.—Duo-cone Type Concrete Mixer.

FIG. 101.—Mixing Chamber of Duo-cone Type Concrete Mixer.

The cheaper grades of lumber are usually used, such as spruce, fir, or even hemlock. Green timber is preferable to seasoned timber, since it is less apt to be affected by the water in the concrete. Better grades of lumber are often used when a particularly smooth finish is desired or where form lumber or sectional forms are used repeatedly. Oiling of the surface of the lumber is beneficial when it is to be used repeatedly, and plank planed on one side is practically essential. Tongued-and-grooved lumber is often used for the sake of water-tightness, but lumber beveled on one edge is considered preferable by many engineers because the edges crush as the wood swells, thus preventing buckling. Forms should always be wetted just prior to the deposition of the concrete.

182. Transportation and Deposition in Forms. The one essential in the transportation of concrete from the place of mixing to the forms is that no opportunity be afforded for a segregation to take place between the mortar and the coarse aggregate. Chutes down which the concrete flows are often considered objectionable, if of any considerable length, for just this reason. Chutes may be so constructed, however, by making the slope conform to the degree of wetness of the mix, that little difficulty is encountered by reason of segregation.

Most commonly, concrete on small work is transported in wheelbarrows or, in case of very thin walls, in hand buckets. On larger work with machine mixers, derricks which swing large dump-buckets, or cars carrying dump-buckets, are commonly used. With modern fairly slow-setting cement there is little danger of the concrete setting before reaching the place of deposition except in case of interruption of the work, in which event especial care must be exercised to see that no concrete be left in wheel-barrows or other conveyences. Regauging of concrete which has set or partially set, by stirring up the mass with or without additional water, is never permissible.

Concrete should be deposited in nearly horizontal layers only a few inches thick and should never be allowed to flow down a slope, since in that event segregation of the fine and coarse material will invariably take place. On work where absolute continuity of the concrete is required the deposition must be carried on continuously until the work is completed. There will invariably be a joint or plane of weakness where one day's work is stopped and deposition of new concrete resumed after twelve to fifteen hours. It is therefore important that the work be so planned and prosecuted that the planes of weakness lie in the direction of least stress in the finished structure. For instance, in an arch the planes should run longitudinally and not transversely.

183. Consistency, Ramming or Puddling. The materials should be mixed wet enough to produce a concrete of such a consistency as will flow into the forms and about the reinforcement if such be present. At the same time it must not be so wet as to cause difficulty through segregation of the coarse aggregate and the mortar before final deposition.

Formerly, it was the practice to mix concrete so dry that an excessive amount of tamping was necessary to compact the mass and prevent bridging of the fragments of the larger aggregate, causing voids.

Specifications now usually require a mix so wet that ramming or tamping is unnecessary, a dense concrete and smooth surfaces being obtained by simply puddling the mass with a straight shovel or slicing tool until the ingredients have settled into their proper place by gravity and any surplus water has been forced to the surface. In order to have a good finish it is well to make use of a straight shovel along each side of the forms, forcing all the larger fragments of the aggregate a short distance back from the face.

184. Bonding to Old Work. Since joints cannot be avoided in work not carried on continuously to completion, every reasonable precaution should be taken to make the bond of new to old work as strong as possible.

In massive work with horizontal joints the question is one of less importance than in thin walls or situations requiring water-tightness. In the former case it will probably suffice to simply clean and wet the old work before laying new concrete. Where walls are thin, or waterproofness is required, the concrete previously placed should be roughened, thoroughly cleaned of foreign material and " laitance," and slushed with a thin grout of either neat cement or rich mortar, the proportion of sand to cement in the latter case not exceeding two to one.

Laitance is a whitish scum which is washed out of concrete when there is excess of water, as when concrete is deposited in water or when water collects in pools on the surface of freshly laid concrete. The laitance consists of the finest flocculent matter in the cement together with dirt from the aggregates, and its formation will be understood by reference to the discussion of the formation of amorphous hydrates during the setting of cement. The composition of laitance is practically identical with the composition of the cement itself. This flocculent material remains suspended in the water for a long time, giving it a milky appearance, and settles slowly on the surface of the concrete. The laitance hardens only very slowly and never acquires much strength, so that, if not removed, it seriously interferes with the bonding of successive layers of concrete.

185. Facing of Walls. The cheapest and most satisfactory method of obtaining a smooth mortar face on concrete walls has already been indicated, namely, by the use of a straight shovel or slice bar along the forms, forcing the coarser aggregate back from the surface.

Plastering with mortar after removal of forms is useless, because it will almost invariably scale off, owing to poor bond and unequal expansion.

Imperfections in the face must, of course, be patched up, but this should be done with a mortar of the same mix as that used in the concrete to prevent different-colored patches showing.

Washing with a thin grout immediately after removal of forms is beneficial to some extent, and if the layer is not of appreciable thickness so as to form a continuous film it will not scale off.

A layer of special mortar is sometimes placed next the forms by means of a movable sheet-steel diaphragm which is inserted in the form and kept the required distance from the face by suitable spacing blocks. The concrete and mortar are now filled in simultaneously, and the diaphragm is raised as the work proceeds, so that it is always only a few inches below the surface. In this manner the two mixes come into contact with each other before setting begins and the bond will not be imperfect.

A " rubbed finish " is sometimes obtained by removal of the forms while the concrete is still green and rubbing with a wooden float. A " tooled finish " is sometimes produced after the concrete has partially hardened, by use of the tools which are used in finishing stone. A " brushed finish " is produced by brushing the green concrete with a stiff wire brush, after which a dilute solution of hydrochloric or muriatic acid is applied with a brush. The acid thoroughly cleans the stone and brings out the natural colors, but must be immediately removed by slushing with water. Otherwise acid discoloration will occur.

186. Depositing under Water. In many classes of subaqueous concrete construction it is possible to use cofferdams or caissons from which the water may be excluded. The placing of the concrete will then not differ materially from methods commonly used on land. When such methods are not feasible, the problem becomes one of some difficulty, owing to the formation of laitance.

Cement, sand, and stone are of course heavy enough to sink in water, but the laitance and some cement which is not immediately hydrated will be floated away. This therefore represents a considerable loss of cement. The problem is entirely one of placing the concrete in its final position under water without allowing the excessive formation of laitance or washing out of cement.

Many methods have been used with a greater or lesser degree of success, among which the following may be mentioned:

The " tremie," a device often used, consists of a large tube of wood or sheet metal, so constructed as to make its length adjustable, and provided with a hopper at the top. In use the tremie is supported vertically in the water by barges or derricks, provision being made for horizontal movement of the tube over the area occupied by the work. The lower end is allowed to rest on the bottom or is closed by a valve arrangement, and the tube is filled with concrete. The tremie is now lifted a few inches or feet and the concrete allowed to escape as the device is moved over the required area. A layer of concrete of any desired thickness is thus deposited, the tube being kept continuously filled to a point above the water line. Of course this method does not entirely prevent the formation of laitance and loss of cement, but it has been found satisfactory on many large works.

Buckets, so constructed as to allow the material to flow out from the bottom, the top being closed, are used in a manner similar to the use of the tremie. A derrick lowers the closed bucket into place, the bottom doors are opened, and the material escapes as the bucket is hoisted. Buckets so used are usually of large capacity, since if several yards of concrete escape at once the material compacts better with less loss of cement.

Bags of all kinds from paper to burlap and heavy jute have been employed in depositing subaqueous concrete. Paper bags are usually of a brown paper which is destroyed shortly after immersion. Cloth bags are not removed or destroyed but, the cloth being very porous, enough cement escapes to bind the bags quite firmly together. Bags are never filled completely, as it is desirable to have them pack together closely.

Concrete is sometimes mixed and deposited in water altogether dry, sacks or buckets being used. This method is entirely unsatisfactory, as the escape of cement is very great and it is impossible to obtain as uniform and dense a concrete as is obtained by any of the above methods, using concrete mixed with water in the usual manner.

THE MAKING OF CONCRETE UNDER SPECIAL CONDITIONS

Laying Concrete in Freezing Weather

187. Effect of Low Temperatures. It has been shown above (Art. 122) that low temperatures have a marked effect in increasing the setting time of cement, often from four to eight times as long a period being required to obtain a final set at a temperature of 32° F. as is required at normal temperatures. If water in concrete or mortar freezes before the cement has set, it is not available for the chemical action of setting and hardening and hence the concrete or mortar will not set at all until the ice melts. The above facts must be borne in mind when removing forms from concrete placed during cold weather.

If the temperature hovers above the freezing-point for some time after concrete is deposited, there is a possibility of the water drying out before the greatly delayed setting has taken place. If, however, the concrete has begun to set before the temperature drops considerably below the freezing-point, the expansion of the water in solidifying produces an expansive force in excess of the cohesive strength of the green concrete. This action results in destruction of the bond and crumbling of the concrete when the ice melts.

If the temperature does not fall more than a degree or two below freezing, the result may simply be the further delaying of the set without appreciable injury. This is possible because the water may not have frozen, owing to the chemical heat of combination afforded by the slowly setting cement. Experiments made by Mr. E. R. Mathews and Mr. James Watson * led to the following conclusions:

> (1) Light frost (not more than about 3° F. below freezing) has a permanently injurious effect on cement if it occurs immediately after gauging, a lesser detrimental effect which is not permanent when it occurs twenty-four hours after the cement is gauged, and no effect after forty-eight hours.
>
> (2) Heavy frost (about 17° F.) has a permanent most injurious effect upon cement and mortar freshly mixed.
>
> (3) The injurious effect of light frost on mortars occurs more immediately than on neat cement, but the mortar recovers from the ill effect more rapidly.
>
> (4) The gauging of cement and mortar with warm water (100° F.) has a permanently injurious effect upon cement and mortar.

188. Methods of Concreting in Freezing Weather. "Concrete should not be mixed or deposited at a freezing temperature, unless special precautions are taken to avoid the use of materials containing frost or covered with ice crystals, and to provide means to prevent the concrete from freezing after being placed in position and until it has thoroughly hardened."

Work may be carried on during freezing weather by either of two methods—keeping the materials and the work at a temperature above the freezing-point until the concrete has had time to set, or, for temperatures only a few degrees below freezing, by the addition to the water used in mixing of a substance which lowers the freezing-point of water.

The first method is more generally recommended and used. The

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* Trans. Am. Soc. C.E., Vol. 64, p. 320.

sand and stone are heated by piling them over heated iron conduits or steam pipes, and the water is heated in a large supply tank fitted with steam coils. The tests quoted in the above article would indicate that there is perhaps some danger of having the water and other materials too hot at the time of mixing.

The work may be protected from frost by covering with earth, canvas, boards, etc., if the temperature falls but very little below freezing, but in case of heavy frost heat must be artificially supplied. One of the most common and efficient methods consists in covering the top of the work to a depth of several inches or a foot with manure, which is in turn covered with boards or canvas. The chemical action of decomposition of the manure is a source of sufficient heat to prevent frost reaching the work.

When the work is in the nature of a building or structure of limited extent it is practicable to house the work with sheathing or canvas. Fires are then kept going continuously in salamanders within the enclosure, thus keeping the temperature above freezing.

The second method, by reducing the freezing-point of water, is not generally considered as favorably as the above-described methods, but is cheaper and hence often used. Common salt or calcium chloride is most commonly used. Approximately 1 per cent of salt in the mixing water lowers the freezing-point 1° F. Beyond 10 per cent salt becomes ineffective and decidedly injurious. It has not been conclusively shown, however, that small percentages are injurious. Alcohol, glycerine, and other chemicals have an effect similar to that of salt in reducing the freezing-point of a water solution. All are, however, less effective than salt, and the latter being cheaper is commonly preferred.

CONCRETE IN SEA WATER. EFFECT OF ALKALI ON CONCRETE

189. Action of Sea Water on Concrete. The behavior of concrete in sea water is a problem which has occupied much of the attention of engineers for many years. The question has often been discussed, and many attempts have been made to determine experimentally the exact action of sea water upon concrete, and the causes of that action. The amount of accurate information available is rather meager, however, and the results of experimental investigations are inconclusive and often contradictory.

Many concrete structures in sea water have remained intact and uninjured for many years; a few, constituting a small minority of all marine structures built, have been injured or destroyed under the same conditions. In view of the conflicting results obtained experimentally it is difficult or impossible to explain why certain marine structures remain sound indefinitely, while others disintegrate more or less rapidly.

We know that the salts in the sea water (magnesium sulphate, magnesium chloride, sodium chloride, and calcium sulphate) react in some way with the constituents of cement. It appears further that cements high in free lime or especially high in alumina are especially subject to the destructive attack of the salts in the sea water. Beyond this general statement we are not willing to attempt any explanation of the chemical action involved.

In view of the recently acquired more definite knowledge of the constitution of cement and the chemical processes of hydration, a reasonable explanation of the chemical action of sea water upon concrete may soon be forthcoming. All attempted explanations have hitherto been predicated upon an imperfect knowledge of constitution and are in consequence untrustworthy.

The chemical action is accompanied by various physical phenomena: sometimes the mass swells, cracks, and gradually falls apart, sometimes the mortar softens and gradually disintegrates, and occasionally a crust forms on the surface which later cracks off. Often the disintegration is facilitated by freezing or by imperfect construction, especially when proper means have not been taken to prevent the inclusion of the laitance, which forms to a much greater extent in salt water than in fresh water.

190. Expedients Adopted to Prevent Injury by Sea Water. Foremost among the precautionary measures to be taken in the construction of marine structures of concrete is the securing of as dense and impermeable a concrete as possible. This end may be secured by any of the means discussed in Art. 192 and sequence.

An outer shell of especially dense materials is sometimes used with good results on marine structures. In this case a few inches of rich mortar (1 : 2 or 1 : 2½) is made to enclose and protect the inner portion of the concrete. It is of course necessary that this outer layer be cast at the same time as the inner portion in order that there may be a perfect bond between the two mixes.

Sometimes certain substances, such as barium chloride, are dissolved in the mixing water for the mortar used on the outer shell. These, upon contact with the salts of the sea water, form insoluble sulphates which tend to close the pores in the mortar.

Sesquicarbonate of ammonia or magnesium fluosilicate are sometimes used as a coating applied to the face of the finished work by brush or spray. These tend to form an impervious film of carbonate of lime in the one case, and insoluble calcium fluoride and lime silicate in the second case, thus stopping the pores. Of course the latter methods remain effective only just so long as the impervious coating remains intact.

191. Effect of Alkali on Concrete. The effect of alkali on concrete is a problem resembling in many respects that of the action of sea water on concrete. The problem is of especial interest in connection with concrete construction in the arid regions of the West, where soluble salts are present in the soil to an extent not usually found elsewhere.

The principal salts encountered in alkali waters usually include: magnesium sulphate, calcium sulphate and sodium sulphate, magnesium chloride, sodium chloride, and potassium chloride, together with carbonates of magnesium, sodium, and potassium. Of these the sulphates appear to be most active in causing disintegration of concrete; the chlorides also are active, while the carbonates appear to be without effect.

The attempts at an explanation of the manner of attack of these salts upon concrete have hitherto encountered the same difficulty found in the case of sea water—an unsatisfactory knowledge of the constitution of cement. From the physical point of view the action exactly resembles the action of frost, except that it is more rapid. There exists, apparently, a disruptive force which quickly destroys the bond and causes disintegration. This action appears to proceed most rapidly in the parts of a structure subjected to alternate wetting with alkali water and drying in the air. In porous concrete the action proceeds much more rapidly than in dense concrete, where, indeed, it may make no progress at all.

As in the case of the injurious action of sea water on concrete, instances of failure caused by alkali waters are merely isolated ones, presenting an interesting field for study, but not constituting a very serious menace to the future of concrete construction in the arid regions of the west. The remedy in the present state of our knowledge is, as in the case of marine structures, a matter of the possible physical precautions only—the securing of the densest possible concrete, thus preventing injury by the exclusion of the salt-bearing waters.

CONCRETE WHERE WATER TIGHTNESS IS REQUIRED

192. Proportioning the Mixture. The permeability of concrete is closely related to the porosity or void content, but the relationship is not always direct and by no means constant, since the continuity and size of the pores determines permeability more than does the actual percentage of voids.

Dense concrete may, as above noted, be most readily obtained by a careful proportioning of the mixture based on careful selection and mechanical analysis of the aggregates. Mixing several of different granulometric compositions to obtain one having a minimum void space may sometimes be resorted to on important work. Usually only the outer layer having a thickness of a few inches need be thus carefully proportioned. It may even be advisable for this outer shell, to use a mortar of 1 : 2 mix, in which case with careful deposition practical imperviousness may be secured.

193. Thickness Required for Water Tightness. The thickness required for a water-tight wall or waterproofing layer on heavy walls, etc., will of course depend upon the mix used, the care exercised in the selection of the aggregates and in depositing the concrete, and the pressure or head of water encountered.

A 1 : 2 mortar carefully made with selected materials need not be more than 2 to 4 inches thick to remain practically water tight under all heads up to 40 or 50 feet;

A 1 : 2 : 4 concrete carefully made of selected materials will be practically water tight under heads up to 50 feet when not more than 1 foot thick; and

An average 1 : 2 : 4 concrete made under average conditions without more than common intelligent selection of aggregates will be practically water tight under heads up to 10 feet when the thickness is made from 1 foot to 1½ feet.

194. Use of Waterproofing Compounds. Waterproofing compounds may be classed in two general divisions: Inert fillers—that is, those materials such as clay, finely ground sand or feldspar, hydrated dolomitic lime, etc., which serve simply as void fillers and do not have any action upon the cement nor change in themselves—and active fillers, which react with certain of the constituents of the cement to form inert insoluble compounds, or in the presence of the cement react with water and precipitate insoluble compounds. In this latter class are included many patented compounds all consisting essentially of stearic acid combined with soda and potash or lime.

Inert fillers are added to the dry cement before mixing the mortar or concrete in percentages usually amounting to from 10 to 20 per cent of the weight of the cement. Active fillers are also mixed with the dry cement before mixing, but the percentage used is not often more than 2 per cent by weight of the cement. Upon the addition of water to a stearate of lime, a lime-soap is formed which is not only insoluble in water, but is not wet by the water. Hence these compounds are often spoken of as " water-repelling compounds." In case the stearic acid is combined with soda or potash, instead of lime, the soda-soap or potash-soap is readily soluble, and these must combine with the lime in the compound to form the insoluble lime-soap. This is readily accomplished, since the stearates in the compounds never amount to more than a very small percentage, the greater part of the material being hydrated lime and magnesia.

All of the inert fillers are fairly effective in reducing permeability, clays being slightly more effective than ground sand or feldspar. The active fillers are also usually more or less effective in reducing permeability, though often to a lesser degree than some of the inert materials. The inert fillers have little effect upon either tensile or compressive strength of mortars and concretes. In fact, the clay in particular sometimes appears to be beneficial to strength. The active fillers, on the other hand, usually reduce both the tensile and the compressive strength of rich mortars (i.e., not leaner than 1 : 4) and only in very lean mixtures is their injurious effect upon strength no longer noted.

Hydrated lime used in amounts not exceeding 10 to 15 per cent of the cement is one of the best materials for waterproofing concrete available. Its action, as above noted (Art. 145), appears to be chiefly mechanical, in that it produces a fat, viscous mortar in which separation of sand and cement is reduced to a minimum and a uniform dense concrete secured.

195. Layers of Waterproof Material. Layers of waterproof paper or felt applied with a coating of coal tar or asphalt are sometimes used as an impervious course in underground concrete walls, floors, etc. Asphalt is much superior to coal tar, since the latter deteriorates when long exposed to moisture. The asphalt is spread hot on the concrete already placed, followed by alternate layers of paper or felt and hot asphalt. Usually the waterproof course is laid 3-ply, 4-ply, or even 5- or 6-ply.

Such a course is finally coated with asphalt again, and the remainder of the concrete deposited in place at once. A distinct joint in the masonry is necessarily formed in the plane of the impervious course, and this fact must not be overlooked in designing walls and floors in which a waterproof layer is incorporated.

196. Surface Treatments for Waterproofing. The principal classes of coating compounds are the following:

(1) *Oil Paints and Varnishes.* These are usually not specially made for use as cement paints, but are ordinary paints consisting of resins, pigments, driers, etc., mixed with linseed oil. They are superficial, inelastic, short lived, and of little value.

(2) *Bitumens.* These include asphalt, petroleum residuum, and coal-tar pitches. All are applied as a hot liquid with or without waterproof paper or felt, and become solid at ordinary temperatures. Bitumens give fairly satisfactory results owing to their great elasticity and durability except when exposed to the weather.

(3) *Liquid Hydrocarbons.* These include solutions of paraffin in benzine or benzol, and emulsions of petroleum oil or fat in water secured by the use of ammonia. They are superficial, but may prove effectual until their efficiency is destroyed by the opening up of small surface cracks on the face of the masonry.

(4) *Soaps.* Soaps are used either solid or in solution, and also in connection with alum. They are soluble in water, so their efficiency is limited to the possibility of chemical action resulting in the formation of insoluble lime-soap.

(5) *Cements in which Water-repellent Material has been Incorporated during Manufacture.* These may be used as an exterior coating, or they may be incorporated in the entire concrete. They differ in no respect from ordinary cement with which one of this class of waterproofing compounds has been mixed just prior to concrete or mortar mixing, and hence need not be separately discussed here.

PROPERTIES OF CONCRETE

197. Compressive Strength. The compressive strength of concrete is dependent upon many factors which vary widely. All of the factors which affect the strength of cement mortars naturally affect concrete in a similar manner. The density, the character and granulometric composition of the aggregate, the consistency of the mixture, the actual mechanical strength of the stone of the aggregate, and the conditions of mixing, deposition, and aging all have a direct bearing upon the strength of concrete. Thus it is impracticable to attempt to state the average strength of given mixes of concrete at definite ages in more than a very general way. For any work of large extent it is always desirable to make a series of tests of the actual concrete used, the test specimens being, whenever possible, molded from the concrete actually mixed for the work. If this is not possible, the materials employed on the work should be used, and the conditions of mixing, etc., made to approximate those which will obtain on the work as closely as possible.

Fig. 102 is inserted to give an approximate idea of the strength of concretes. The curves express the average results of compressive tests of five concretes made from different brands of Portland cement. The tests were made in 1899 at the Watertown Arsenal.* All specimens were 12-inch cubes, the mixtures used being 1 : 2 : 4, 1 : 3 : 6, and 1 : 6 : 12.

Fig. 103, which is based upon a series of long-time tests of 8-inch concrete cubes of 1 : 2 : 4 mix made by the author, is inserted because a five-year period is covered by the tests. All of the specimens were made from the same mix with a well-known brand of Portland cement. The sand was an average, fairly clean and well-graded natural sand, and the stone was crushed trap rock from which all material under ⅜-inch and over 2½ inches had been screened. The curve given is representative of the results of similar tests made with several different brands of cement. The slight drop in strength after long intervals was found characteristic of practically all tests. Specimens after molding were stored in damp air for forty-eight hours, and were then allowed to harden in air in the laboratory.

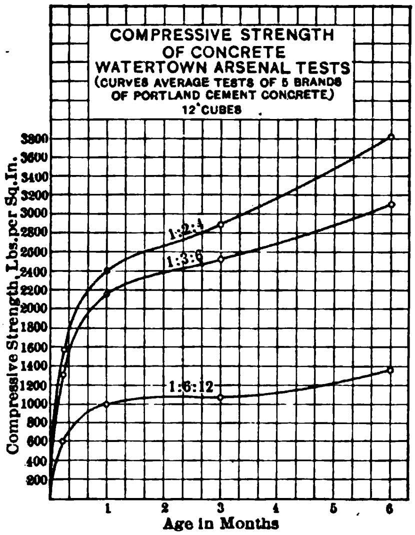

Fig. 102.

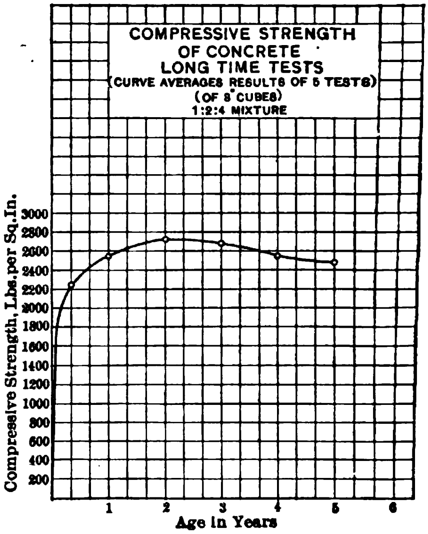

Fig. 103.

198. Tensile Strength. The tensile strength of concrete is a property of limited importance because, being low in comparison with the compressive strength, concrete is practically never designed to withstand tensile stresses. It will usually be found to be more economical

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* Tests of Metals, 1899.

to use steel reinforcement than to depend upon the tensile strength of concrete.

The character of the workmanship and the materials used will greatly influence tensile strength, perhaps to an even greater extent than they affect compressive strength.

The series of tests enumerated in the following table were made by the author upon specimens molded in the field under ordinary field conditions, and shipped to the laboratory for testing. The compressive tests were made upon 6-inch cubes and the tensile tests upon prisms, 6 by 6 inches in cross-section. The mixtures used were of three kinds:

(*a*) *First-class Limestone Concretes.* One part Portland cement, two parts bank sand, and four parts of limestone crushed to pass a 1½-inch ring.

(*b*) *First-class Sandstone Concrete.* Same mix and materials as (*a*) except that cobbles, mostly sandstone, crushed to pass a 2½-inch ring, were used in place of crushed limestone.

(*c*) *Second-class Sandstone Concrete.* Same as (*b*) except that mix was 1 : 2½ : 5 instead of 1 : 2 : 4.

The compression tests were made in the usual manner, the compression surfaces being bedded in plaster of Paris. The tensile tests were made by the use of specially constructed shackles which gripped the specimens by means of hardwood wedges on all four sides. The load was transmitted to the shackles through a spherical joint at either end, thus insuring failure by direct axial tension, and not through a complication of stresses caused by bending action. The majority of the specimens broke at a point well away from the grips, and in every case the failure occurred in a plane practically at right angles to the stress, the break being clean and showing no indication of any stress other than direct tension. Fig. 104 shows one of the tensile specimens after failure, still held by the apparatus used for the tests.

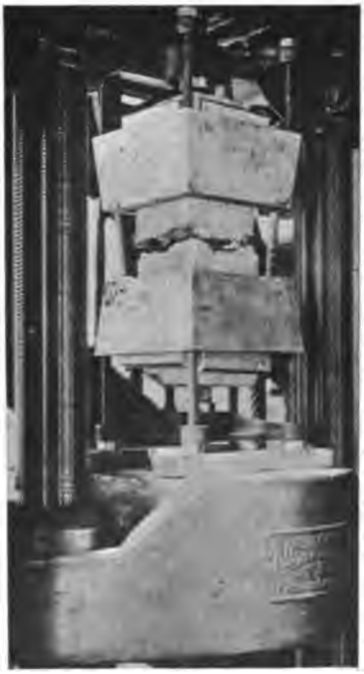

Fig. 104.—Tensile Test of Concrete.

(Note that the values of the ratio of tensile to compressive strength in the following table would have been somewhat lower had the specimens been tested in compression at the same age they were in tension).*

TENSILE AND COMPRESSIVE STRENGTH OF CONCRETE

Quality and Mix.	Approx. Age.		Compressive Strength, Lbs. per Sq.in.	Tensile Strength. Lbs. per Sq.in.	Ratio Tensile Str. Compress Str.
	Tensile Tests.	Compres. Tests			
1st Class Limestone 1 : 2 : 4	6 Mo.	1 Mo.	2206	278	
			2708	308	
			2500	253	
				306	
				264	
				257	
	Average...	....	2505	278	11.1%
1st Class Sandstone 1 : 2 : 4	6 Mo.	1 Mo.	1069	149	
			1375	142	
			1417	133	
			1722	178	
			2000	158	
			2139	128	
				153	
				150	
				161	
	Average...	....	1620	150	9.3%
2d Class Sandstone 1 : 2½ : 5	6 Mo.	2 Mo.	1028	121	
			1639	114	
			972	106	
			889	158	
			1042	114	
			2083	97	
			1472	179	
			1889	129	
			1639	139	
	Average...	....	1406	129	9.1%

199. Transverse Strength. The transverse strength of plain concrete is almost wholly dependent upon the tensile strength of the concrete. Experiments show, however, that the modulus of rupture is considerably greater than the strength in tension. The following table represents the results of transverse strength tests made upon concrete beams 8 inches wide, by 10 inches deep, supported on spans varying from 3 to 8

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* For detailed account of these tests see The Cornell Civil Engineer, Vol. 19, pp. 106–113.

feet. The materials used were a high-testing Portland cement, a fairly clean bank sand of excellent granulometric composition, and crushed trap rock screened to remove all fragments under ¼ inch and over 1 inch in size.

The tests were made in the laboratory of the College of Civil Engineering, Cornell University, under the direction of the author. Each result is the average of from six to eight separate tests made at an age of about three months.

TRANSVERSE STRENGTH OF PLAIN CONCRETE

Mix.	Modulus of Rupture.
1 : 1½ : 3	470
1 : 2 : 4	389
1 : 3 : 6	216
1 : 4 : 8	112

200. Shearing Strength. The shearing strength of concrete is a most important property of the material, since it is the real determining factor in the compressive strength of short columns. The strength of concrete beams is also under certain conditions dependent upon the shearing strength of the material.

Since the angle of shear in concrete compression members must be slightly greater than 45°, we should expect the direct shearing strength to be slightly less than one-half the compressive strength. This theory has been well borne out by experiment as the data of the following table taken from tests made at the University of Illinois will show.*

SHEARING STRENGTH OF CONCRETE
(EACH RESULT THE AVERAGE OF FROM 1 TO 17 TESTS)

Mix.	(S) Shearing Strength, Lbs. per Sq.in.	(C) Compressive Strength Lbs. per Sq.in.	Ratio S/C.
1 : 2 : 4	1193	3210	.37
1 : 2 : 4	1257	3210	.39
Average	1225	3210	.38
1 : 3 : 6	679	1230	.55
1 : 3 : 6	729	1230	.59
1 : 3 : 6	905	2428	.37
1 : 3 : 6	968	1721	.56
1 : 3 : 6	796	1230	65
1 : 3 : 6	692	1230	.56
1 : 3 : 6	879	1230	.71
1 : 3 : 6	1141	2428	.47
1 : 3 : 6	910	1721	.53
Average	856	1605	.53

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* Bull. No. 8 Univ. of Ill. Exp. Sta., p. 24.

201. Elastic Properties. The elastic properties of concrete are of importance not only because of their bearing upon the deformation of concrete structures under load, but also because in the design of reinforced concrete it is necessary to know the relative stresses in the steel and the concrete under like distortions.

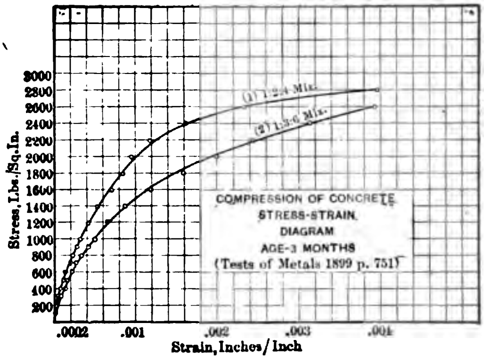

Fig. 105.

Fig. 105 presents typical stress-strain diagrams for short prisms of concrete in compression.

Curve (1) represents 1 : 2 : 4 concrete, and curve (2) represents 1 : 3 : 6 concrete. Both are taken from tests made at Watertown Arsenal in 1899.*

Fig. 106 presents typical load-deflection diagrams for concrete beams under transverse loading. (1) represents 1 : 2 : 4 concrete and (2) represents 1 : 3 : 6 concrete. The tests were made by the author.

It will be seen that the elastic properties of concrete vary with the richness of the mixture and with the intensity of stress. They also vary with the age of the concrete, although this is not shown by the diagrams.

Concrete is not perfectly elastic for any range of loading, an appreciable permanent set occurring for even the smallest loads, and the deformation is not proportional to the stress at any stage of the loading.

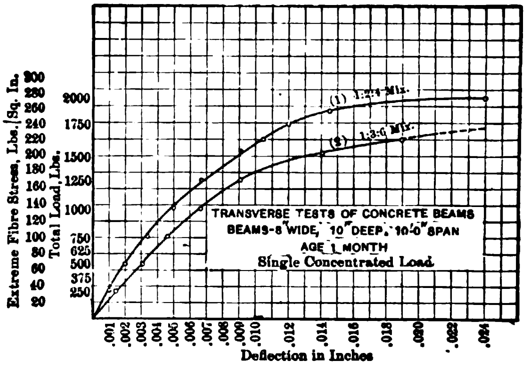

Fig. 106.

202. Modulus of Elasticity. Since, as just stated, the deformation of concrete is not proportional to the stress at any stage of the loading, the modulus of elasticity is not a constant for any appreciable range of stress, but varies from point to point, decreasing as the load increases.

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* Tests of Metals, 1899, p. 751.

The modulus is higher for richer mixtures and increases with the age of the concrete.

The instantaneous value of the modulus may be computed on the basis of the slope of the chord drawn between two points on the stress-strain curve representing a change of stress not exceeding a few hundred pounds. For instance, the modulus at a stress of 300 pounds for the 1 : 2 : 4 concrete of Fig. 105 will be determined by dividing the stress increment from 100 to 500 pounds per square inch by the strain increment for that same range (i.e., at six months $E = 400 \div 0.00012 = 3{,}300{,}000$ pounds per square inch). Similarly at a stress of 1000 pounds per square inch the modulus is about 2,200,000 pounds per square inch. For the 1 : 3 : 6 concrete of Fig. 105 the modulus at three months is about 2,200,000 pounds per square inch at a stress of 300 pounds per square inch, and about 1,250,000 pounds per square inch at a stress of 1000 pounds per square inch.

The value of the modulus which is of importance in design and construction of concrete is that which corresponds to the working stress of the concrete. Assuming the concrete to be about one to two months old and the working stress not in excess of 500 pounds per square inch, the value of the modulus to be used will be about 2,000,000 to 2,500,000 pounds per square inch for 1 : 2 : 4 mix, and 1,500,000 to 2,000,000 pounds per square inch for the concrete of 1 : 3 : 6 mix.

203. Elastic Limit. As stated in Art. 201, concrete shows a permanent set under the smallest loads. There can therefore be no elastic limit in the true sense of the term. There appears to be a stress, however, below which repetition of the same load does not cause appreciable increase in set, while beyond this stress repetition of load causes increased set indefinitely, finally resulting in rupture far below the normal ultimate strength. For practical purposes, therefore, it is convenient to consider this stress as the elastic limit. Experiments made by Bach, Van Ornum, and others seem to place this stress at about 50 to 60 per cent of the ultimate strength.

204. Stress-strain Curves. The curves of Fig. 105 are typical stress-strain curves for concrete in compression. These curves have often been found to approximate closely to parabolas the axis of which is vertical, the origin being located at the point representing the ultimate strength.

This fact has been made the basis of some methods of concrete beam design wherein the variation in stress in the concrete is assumed to be parabolic from the neutral axis to the extreme fiber. This means that the design is really based upon the ultimate strength of the material. This method has been replaced to a great extent by methods which assume the stress-strain curve to be a straight line for stresses under the allowable working stress. The computations required are thus simplified, and the design is based upon safe working stresses instead of the ultimate strength of the material.

205. Coefficient of Expansion. The coefficient of expansion of 1 : 2 : 4 concrete has been determined by several investigators with considerable uniformity to be about 0.0000055 per degree Fahrenheit. Other experiments have placed the coefficient of expansion of 1 : 3 : 6 concrete at about 0.0000065. These values differ so slightly from the coefficient of expansion of steel that there is little danger of failure of the bond of concrete and steel in reinforced concrete by reason of temperature changes and the resultant volumetric changes.

206. Contraction and Expansion of Concrete. In addition to the volumetric changes due to temperature variation, concrete is subject to other volume changes caused, as in the case of mortars (Art. 160), by the chemical processes of setting and hardening or by variation in the moisture content. Experiments made to determine the expansion and contraction of concrete while hardening are not numerous, but they show conclusively that concrete hardened in air contracts, and concrete hardened in water expands, the amount of change in volume being dependent upon the richness of the mixture. Experiments made by White (Art. 160) indicate that the expansion or contraction even in the case of old concrete, when alternately wet and dried, is far from being negligible. Pieces of concrete, presumably not leaner than 1 : 3 : 6 or richer than 1 : 2 : 4, sawn from a sidewalk after twenty years in service, showed an expansion of 0.05 and 0.06 per cent when placed in water, and the same expansion when subsequently allowed to dry in air.

If this concrete were restrained so that no volume change could take place, the resultant stresses introduced, considering the modulus of elasticity of the cement to be 2,000,000 pounds per square inch, would amount to from 1000 to 1200 pounds per square inch, a stress probably equal to at least half the ultimate strength if in compression, and far exceeding the ultimate strength if in tension.

207. Weight of Concrete. The weight of concrete is a factor in design, in that it must be included in the dead load on any structure. The weight is dependent almost entirely upon the denseness of the concrete. If the aggregate, both fine and coarse, be of very well-graded composition and the concrete deposited in a manner to insure the minimum of void space, the weight may run as high as 160 pounds per cubic foot, and for less carefully chosen materials or less perfectly executed work the weight may not exceed 140 pounds per cubic foot. For practical purposes of design it is customary to assume the weight of concrete to be 150 pounds per cubic foot.

208. Adhesion of Steel. The adhesion of concrete to steel is chiefly important in it's bearing on the design of reinforced concrete. The bond strength is dependent principally upon the richness of the mix and the character of the surface of the steel. The following table based upon tests made at the University of Illinois in 1906 gives representative values of the bond between concrete and steel rods.*

ADHESION OF CONCRETE TO STEEL RODS

Mix.	Steel Rods.			Adhesive Strength, Lbs. per Sq.in.
	Kind.	Size, Inches.	Depth Embedded, Inches.	
1 : 2 : 4	Plain round....	½ and ⅝	6	438
1 : 2 : 4	Plain round....	½ and ⅝	12	409
1 : 3 : 5½	Plain round....	½ and ⅝	6	364
1 : 3 : 5½	Plain round....	½ and ⅝	12	388
1 : 3 : 5½	Cold rolled shafting.....	1 and ½	6	146
1 : 3 : 5½	Mild steel flat..	$\frac{3}{16}\times 1\frac{1}{2}$	6	125
1 : 3 : 6	Tool steel round	¾	6	147

The adhesive strength of 1 : 2 : 4 concrete to plain round rods appears to be about 400 pounds per square inch. In situations where a higher bond strength is required it is customary to secure a mechanical bond by the use of some form of deformed bar.

209. Ratio E_c/E_s. The relative moduli of elasticity of concrete and steel determine the relative stersses in the two materials when the combined concrete and steel member is deformed a given amount. So long as the bond is not destroyed the ratio E_c/E_s fixes exactly the relative stresses in the concrete and steel. E_c for 1 : 2 : 4 concrete, the mix almost exclusively used for reinforced concrete, has been stated to be about 2,000,000 pounds per square inch (Art. 202), and for steel E_s is about 30,000,000 pounds per square inch. The value of the ratio E_c/E_s is, therefore about 1/15.

210. Fire Resistant Properties of Concrete. Concrete as a fire resistant has been subjected to various experimental trials, but the best proof of its value so used lies in the experience afforded by many very severe fires wherein concrete well demonstrated its superiority over most other materials, which are used for fire protection.

The value of concrete as a protection for steel work in case of fire is due to several considerations. In the first place, concrete is in itself incombustible; second, its temperature coefficient is practically the same

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* Bull. No. 8 Univ. of Ill. Eng. Exp. Sta.

as that of steel, thus giving it an advantage over materials like terra cotta, which expands much more rapidly than does steel, and hence tends to fail by reason of the destruction of the bond caused by unequal expansion; third, the rate of heat conductivity of concrete is very low, due in part to its porosity and consequent air content, and in part to the dehydration of the water of chemical combination, the volatilization of which absorbs heat. This latter action increases the porosity, and hence the conductivity of the concrete which has suffered dehydration is still further lowered, and the penetration of the dehydrating action proceeds very slowly.

The concrete which thus becomes dehydrated is seriously injured, but the effect is seldom appreciable to a depth of more than a small fraction of an inch, except in the hottest- and longest-burning fires. Concrete called " cinder concrete," in which the usual coarse stone aggregate has been replaced by cinders, has been found quite as effective a fire resistant as is stone concrete.

In general it is considered that a covering of concrete over steel work, 2 inches in thickness, is sufficient to effectually protect the steel against temperatures sufficiently high to cause warping and twisting, with consequent failure of the structure.

211. Protection of Steel from Corrosion. Experience gained at the time of the demolition of reinforced concrete structures after years of exposure in damp situations, and carefully conducted experiments, as well, have shown that concrete forms a most effective preventive of the corrosion of steel imbedded therein. Particularly is this true if the concrete be mixed sufficiently wet so that the steel is completely covered by a wash of thin grout.*

Experiments made by Professor Charles L. Norton for the Insurance Engineering Station in Boston led to the following conclusions:

" (1) Neat Portland cement, even in thin layers, is an effective preventive of rusting.

" (2) Concretes, to be effective in preventing rust, must be dense and without voids or cracks. They should be mixed quite wet where applied to the metal.

" (3) The corrosion found in cinder concrete is mainly due to the iron oxide, or rust, in the cinders and not to the sulphur.

" (4) Cinder concrete, if free from voids and well rammed when wet, is about as effective as stone concrete in protecting steel."

212. Working Stresses and Factor of Safety. The following working stresses are recommended by the Committee on Concrete and Reinforced Concrete of the American Society of Civil Engineers.†

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* See Trans. Am. Soc. C.E., Vol. 71, p. 200.

† Trans. Am. Soc. C.E., Vol. 66, p. 431.

The allowable compressive stress "on a plain concrete column or pier, the length of which does not exceed twelve diameters, is 22.5 per cent of the compressive strength at twenty-eight days, or 450 pounds per square inch on 2000-pound concrete." The factor on the basis of the twenty-eight day strength is therefore about 4.5.

"The extreme fiber stress of a beam, calculated on the assumption of a constant modulus of elasticity for concrete under working stresses, may be allowed to reach 32.5 per cent of the compressive strength at twenty-eight days, or 650 pounds per square inch for 2000-pound concrete." The apparent factor is about 3.1. (The actual factor is considerably larger.)

"Where pure shearing stress occurs, that is, uncombined with compression normal to the shearing surface, and with all tension normal to the shearing plane provided for by reinforcement, a shearing stress of 6 per cent of the compressive strength at twenty-eight days, or 120 pounds per square inch on 2000-pound concrete may be allowed." The factor here is about 6 or 7.

"Where the shear is combined with an equal compression, as on a section of a column at 45 degrees with the axis, the stress may equal one-half the compressive stress allowed. For ratios of compressive stress to shear between 0 and 1, proportionate shearing stresses shall be used." The factor is here again about 4.5.

"The bonding stress between concrete and plain reinforcing bars may be assumed at 4 per cent of the compressive strength at twenty-eight days, or 80 pounds per square inch for 2000-pound concrete; in the case of drawn wire, 2 per cent, or 40 pounds per square inch on 2000-pound concrete." The factors are here about 4.5 and 2.25 respectively.

"It is recommended that . . . the modulus of elasticity of concrete . . . be assumed as one-fifteenth that of steel, as, while not rigorously accurate, this assumption will give safe results."

NON-CEMENTING MASONRY MATERIALS

CHAPTER IX

BUILDING STONES AND STONE MASONRY

BUILDING STONES

GENERAL

213. Stone as a Structural Material. The term "building stone" is applied to all those classes of natural rock which are employed in masonry construction. Stones form, with the exception of timber, the only important class of materials which may without alteration of their natural state be used directly in the construction of engineering works.

Stone has been employed since prehistoric times in the construction of walls, dwellings, etc. Its use in masonry foundations, dams, piers, and even arches and bridges is very ancient; it has been used as an ornamental material in types of masonry other than stone masonry since these types originated, and in the form of carved stone it has been one of the chief sources of architectural adornment of structures for the architects of all ages.

Aside from purely structural uses, great quantities of stone are utilized on other kinds of engineering construction. Of all the stone quarried in the United States about 40 per cent is used for building and monumental purposes as rough or cut stone, about 5 per cent is used for flagging and curbing, something over 6 per cent for paving blocks, over 21 per cent as crushed stone for road building, nearly 12 per cent as crushed stone railroad ballast, and over 16 per cent as crushed stone concrete aggregate.

214. Classification of Rocks. *Geological Classification.* In the usual geological classification rocks are divided into *Igneous Rocks* formed by consolidation from a fused or semi-fused condition; *Sedimentary Rocks,* formed by the solidification of material transported and deposited by water; and *Metamorphic Rocks,* which are formed by the gradual metamorphism of the structure and character of igneous or sedimentary rocks through the agency of heat, water, pressure, etc. Greenstone, basalt, and lava are common examples of igneous rocks; sandstone, limestone, and shale, of sedimentary rocks; and granite, marble, and slate, of metamorphic rocks.

The geological classification has only a limited bearing upon the consideration of rocks as building stones. Igneous rocks are usually nonlaminated and more or less crystalline or glassy in structure; sedimentary rocks are distinctly laminated and stratified, having, therefore, distinct cleavage planes; metamorphic rocks may or may not be laminated, depending upon the pressure encountered during metamorphism. Most of the metamorphic rocks which have been changed largely through the agency of water and heat are crystalline in structure.

Physical Classification. The following classification of rocks on the basis of physical structure is made by Professor Baker: *

With respect to the structural character of large masses, rocks are divided into *stratified* and *unstratified.* The structure of unstratified rocks is, for the most part, an aggregate of crystalline grains firmly adhering together. Granite, trap, basalt, and lava are examples of this class.

Stratified rocks may be divided into the following classes according to physical structure:

1. Compact crystalline structure (quartz-rock, marble).
2. Slaty structure (clay and hornblende slate).
3. Granular crystalline structure (gneiss, sandstone).
4. Compact granular structure (blue limestone).
5. Porous granular structure (minute shells cemented together).
6. Conglomerate (fragments of one stone embedded in mass of another).

Chemical Classification. Stones are divided according to the chemical nature of their predominating constituents into the following three classes:

1. *Siliceous stones,* in which silica is the predominating chemical constituent. (Granite, syenite, gneiss, mica-slate, greenstone, basalt, trap, porphyry, quartz-rock, hornblende-slate, and sandstone.)
2. *Argillaceous Stones,* in which alumina is the important constituent. (Slate, and graywacke-slate.)
3. *Calcareous stones,* in which carbonate of lime is the predominating constituent. (Marble and limestone.)

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* I. O. Baker, " Masonry Construction."

STONE QUARRYING AND CUTTING

215. Methods of Quarrying. After the exposure of rock by the stripping of the surface soil the quarrying is done by hand tools, by machine tools, by the use of explosives, or by a combination of two or more of these methods.

Hand Methods. Hand methods may be employed when the stone occurs in thin beds. Such stone, which is usually inferior in quality, may be taken out by use of the drill and hammer, wedges, plug and feathers, pick, crowbar, etc. Holes $\frac{3}{8}$ to $\frac{3}{4}$ inch in diameter are drilled a few inches apart in rows. The rock is thereupon split in the plane of the holes by the driving in of wedges or by use of plug and feathers. The plug is a short steel wedge with plane faces, and the feathers are wedges having one cylindrical and one plane side, Fig. 123. When a plug is inserted between two feathers the three will slip into a cylindrical hole, and a great splitting force in one direction only may be exerted by driving the plug. The drills used are either *jumper drills*, the ordinary type of drill which is held by one man and turned between sledge blows struck by a second man, or *churn drills*, which are long heavy drills used without a hammer by one or two men. The drill is lifted, turned, and allowed to fall back in the hole, the force of the blow being due to the impact of the falling drill alone.

Machine Methods. The use of machinery driven by steam, compressed air, or electric motors, is usually combined with hand methods whenever quarrying operations are conducted on any but a very small scale. The commonest application of power-driven machines in the quarry lies in the use of machine drills which cut much more rapidly than hand drills and are usually arranged to work at any angle. Machine drills are of two general types: *Percussion drills*, the cutting tool of which resembles the hand drill and is operated by a piston and automatically turned a small angle between strokes (steam or compressed-air power), and *rotary drills*, which are hollow tubes provided with an annular cutting edge. Rotary drills are sometimes provided with hardened steel teeth which constitute the cutting edge, but more often the annular end of the drill is set with a number of black diamonds which constitute the cutters. These cutters project slightly inside and outside the wall of the tube, so that clearance is provided and water may be forced down through the tube for the purpose of removing the debris which is washed up through the narrow space between the tube and the rock. The solid core of rock which remains within the tube may be broken off and removed from time to time by withdrawing the drill. Holes may be bored to great depths by joining successive lengths of drill-rod and the solid core affords an excellent indication of the exact nature, stratification, etc., of the rock passed through. When it is not desired to preserve the core intact the cutters may be so arranged as to cut a cylindrical hole instead of an annular hole.

When it is desirable that the stone be removed in rectangular blocks advantage is always taken of the natural cleavage planes of the rock. The quarry is worked in benches, the width of which correspond to the dimensions of stones that can be handled, and the height of which corresponds to the thickness of the rock strata. Rows of holes are drilled parallel and perpendicular to the edge of the bench, wedges or plug and feathers are then inserted in the holes, and the blocks of rock thus split along the planes of the holes. "Under-cutting," the drilling of—and use of wedges in—a series of horizontal holes, is resorted to when not rendered needless by the stratification of the rock.

When the rock need not be removed in large or rectangular blocks, particularly when the rock is to be subsequently crushed for road stone, ballast, or concrete aggregate, explosives may be used in the drilled holes.

When stone is quarried for building and monumental purposes on a scale sufficient to justify the use of more elaborate mechanical equipment than the ordinary machine drills, or when very large rectangular blocks of stone are desired, it is the practice to use a special machine called a "channeler." The channeler is a machine operating on rails or guide bars, which operates a gang of cutters with which long and deep, but narrow channels are cut as the machine slowly moves along. The sides of large blocks are thus freed, and the blocks are subsequently freed from their beds by wedging, or undercutting and wedging, as may be necessary.

Explosives. The explosives used include gunpowder, dynamite, and, rarely, nitroglycerine. *Gunpowder* must be the coarse, slow-acting, cheap powder rather than the high-power, quick-acting grade. Gunpowder is exploded by fuse or electric spark. The term *dynamite* is the name applied to any explosive consisting of some granular substance saturated with nitro-glycerine. *Nitro-glycerine* is a fluid produced by mixing glycerine with nitric and sulphuric acid. It is too quick acting for quarrying operations in general, since the rock is shattered rather than split. Its use is dangerous, owing to the ever-present possibility of escape of the fluid from drilled holes through seams in the rock to some distant place where it may lodge and constitute a menace to life during subsequent operations.

Dynamite is called "true dynamite" when the granular absorbent is an inert material; if the absorbent itself contains explosives the mixture is called "false dynamite." True dynamite may contain at least 50 per cent nitro-glycerine. False dynamites may contain not more than 15 per cent nitro-glycerine but the absorbent generally contains large amounts of oxygen which is liberated upon explosion and aids in effecting the complete combustion of the gases arising from the nitroglycerine. The pressure of a little moist sand, clay, or, in the case of nitro-glycerine, a little water, provides sufficient tamping. Dynamite and nitro-glycerine are exploded by means of a percussion cap, which is a hollow copper cylinder about ¼ inch in diameter and from 1 to 2 inches long, filled with a cement consisting of fulminate of mercury mixed with some inert substance. The percussion cap may be ignited by a fuse, but is more commonly ignited by an electric spark.

216. Stone Cutting. *Tools.* The principal tools used in stone cutting are illustrated by Figs. 107 to 124.* Any description beyond that afforded by the figures is unnecessary and their uses are indicated in the discussion which follows.

Surface Dressing.† All stones used in building come under one of three classes:

I. Rough stones.
II. Stones roughly squared and dressed.
III. Stones accurately squared and finely dressed.

The first class includes all stones used as they come from the quarry without any special preparation.

The second class includes stones roughly dressed on beds and joints with the face hammer or axe. The distinction between this class and the third class lies in the closeness of the joints. When the dressing on the joints is such that the general thickness of mortar required is ½ inch or more the stones properly belong to this class.

Three subdivisions of this class may be made, depending on the character of the face of the stone:

(*a*) Quarry-faced stones are stones whose faces are left untouched as they come from the quarry.

(*b*) Pitch-faced stones are those the edges of whose face are made approximately true by use of the pitching chisel.

(*c*) Drafted stones are those whose faces are surrounded by a chisel draft, the space inside being left rough. This method is not ordinarily used on this class of stones.

The third class includes all stone dressed to smooth beds and joints so that the thickness of mortar joints is less than ½ inch.

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* A description of these tools and their use in dressing stone may be found in Vol. 6, Trans. Am. Soc. C.E., also in Baker's "Masonry Construction."

† Trans. Am. Soc. C.E., Vol. 6.

As a rule all of the edges of cut stone are drafted. Inside the draft any of the following methods of dressing the face may be used.

(*a*) Rough pointed; projections ½ or 1 inch. (Used on limestone and granite.)

(*b*) Fine pointed; projections less than ½ inch.

(*c*) Crandalled; effect same as fine pointed except that the tool marks are more regular, ⅛-inch projections.

Cross-crandalled; if worked in both directions.

(*d*) Axed; or pean-hammered; face covered with parallel chisel marks.

(*e*) Tooth-axed; same finish as fine pointed.

(*f*) Bush-hammered; (usually used only on limestone), follows rough pointing and tooth-axing.

(*g*) Rubbed; sawn surfaces smoothed by grit or sandstone, (used on sandstones and marble).

(*h*) Diamond panels; face inside of draft cut to flat pyramidal form.

PROPERTIES OF BUILDING STONES *

GENERAL DESCRIPTION OF STONES

217. Granite. Granite is the term applied to a Plutonic,† igneous rock, whose structure varies from finely granular to coarsely crystalline. Its principal mineral constituents are quartz and feldspar, with varying amounts of mica, hornblende, etc. Its prevailing color is gray, though greenish, yellowish pink, and red shades are found more or less frequently.

Granite is more extensively used as a building stone than any other class of igneous rock. It works with difficulty, due to its hardness and toughness, but its quarrying is usually facilitated by the existence of planes of weakness, the " rift " extending either in vertical or horizontal planes, and secondary planes, " the grain " along which the rock may be less readily split at right angles to the rift. As a rule the quarry rock shows " joints " or fissures in the direction of the rift, and often a secondary series of joints exists in the direction of the grain. The removal of rectangular blocks of large or small dimensions is thus facilitated.

Granite is used for foundations, base courses, columns, and steps

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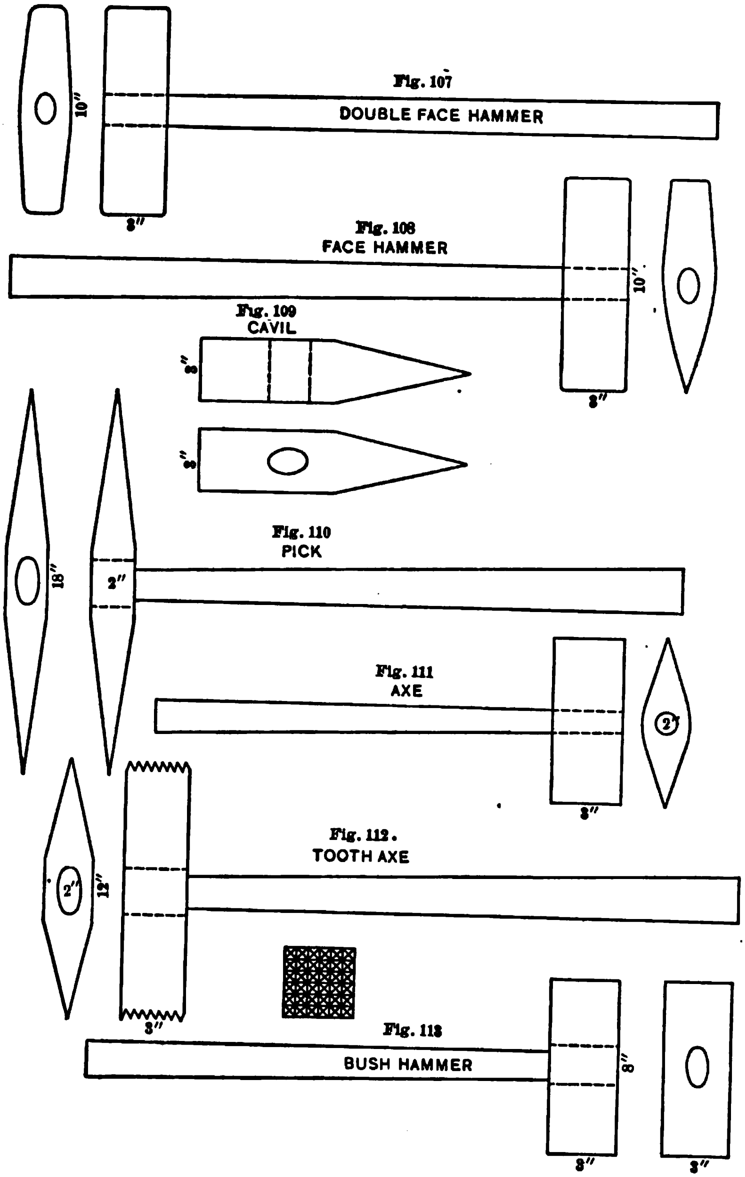
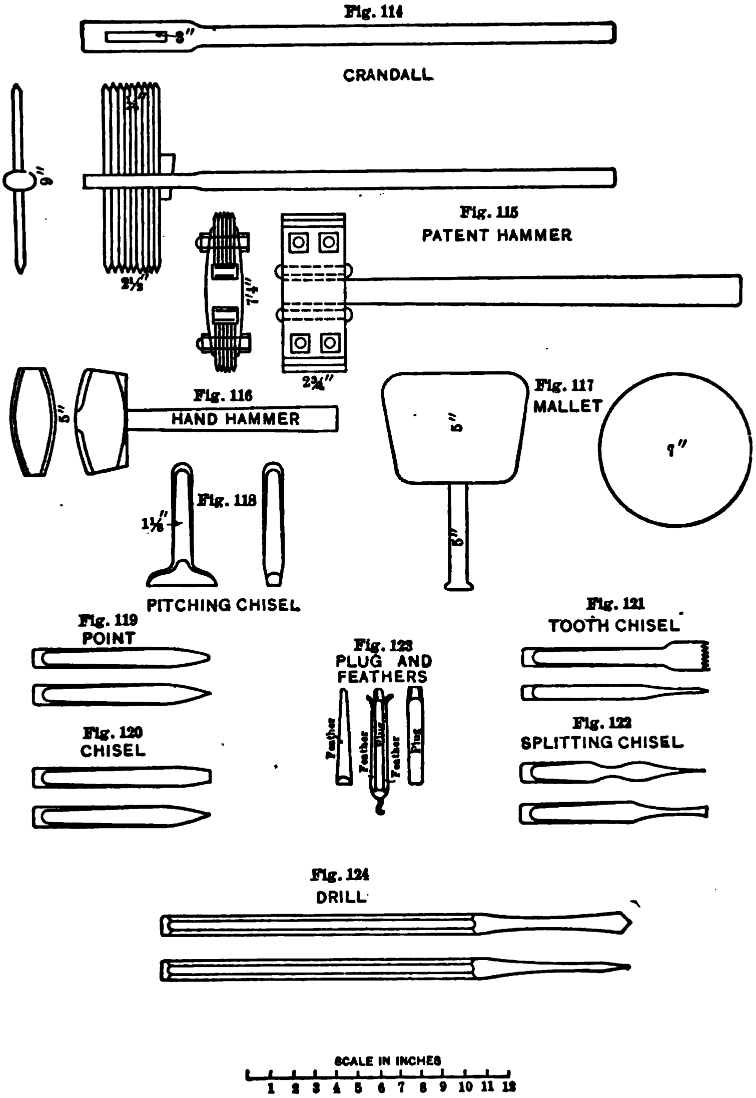
* For detailed information concerning building stones consult " Stone for Building and Decoration " by G. P. Merrill. Also see " Building Stones and Clay Products " by Dr. Heinrich Ries, and " Engineering Geology " by Dr. Ries and Dr. T. L. Watson.

† Plutonic rocks are igneous rocks formed by the solidification of molten material prior to its emergence on the earth's surface, volcanic rocks have cooled on the earth's surface.



Figs. 107–113.—Tools Used in Stone Cutting.



FIGS. 114–124.—Tools Used in Stone Cutting.

in building construction, and is suitable for any situation where strength or hardness is required. To a limited extent it is used as an ornamental stone, this use being confined largely to the softer varieties. Granite of excellent quality may be obtained in any of the New England States, in most of the Southern States, in the Rocky Mountain Region, and in California and Minnesota.

218. Gneiss. Gneiss has the same composition as granite and resembles granite in appearance but differs in physical structure, the various constituents being arranged in more or less parallel layers. The rock therefore splits readily into flat slabs, which renders quarrying less expensive than in the case of granite and makes the stone valuable for foundation walls, street paving, curbing, and flagging. It is found in the same localities as granite.

219. Limestones. The term limestone is commonly applied to all stones which, though differing from one another in color, texture, structure, and origin, possess in common, the property of containing carbonate of lime as the essential constituent. All contain in addition to carbonate of lime a greater or lesser amount of carbonate of magnesia and carbonates or oxides of iron, silica, clay, bituminous matter, mica, or talc, etc. Different limestones may be listed according to structure and composition and mode of origin under the following heads:

220. Crystalline Limestone or Marble. The term "marble" is commonly applied to any limestone which will take a good polish. It is properly applied only to those limestones which have been exposed to metamorphic action and rendered more crystalline in structure, the color being changed or even lost.

The structure of marbles varies from finely crystalline to coarsely crystalline. Marbles are found in almost every conceivable color, and are often richly streaked with several colors. All varieties of marble work well, the finer grained white marble being especially adapted to carving. Marble has been used in this country principally for interior decoration, but many varieties are entirely suitable for exterior construction. Most of the colored and mottled and veined marbles are imported into this country. Quantities of white and black marbles are quarried, however, in Vermont, Tennessee, Georgia, New York, Pennsylvania, Maryland, and California, and some beautiful colored and mottled marbles are obtained from these quarries.

221. Compact Common Limestones. These are fine-grained crystalline limestones which contain many different minerals, giving rise to many varieties. The best known and most widely used American limestone is the *Bedford limestone.* This is a light-colored, fine-grained, oolitic limestone (made up of small rounded concretionary grains cemented together by carbonate of lime). It is a light gray in color, works with remarkable ease, and hardens on exposure. It has been extensively used for exterior construction of buildings, for bridge piers, and for heavy cut-stone masonry in general. It is quarried at Bedford, Indiana, also in Ohio and Illinois. *Travertine* is a compact fine-grained limestone deposited on the surface by running streams and springs. The term *onyx* or *onyx marble* is often applied both to *travertine* and to *stalactite* and *stalagmite*, which are deposits of limestone, often beautifully banded and streaked with colors, formed on the roofs, walls, and floors of caves. This use of the term " onyx," though incorrect, since it properly applies to a banded variety of chalcedony, has come into such general use that it may as well be accepted as referring either to travertine or to stalactite and stalagmite. (Which, is immaterial, since the three are identical in composition and appearance, differing only in manner of chemical deposition).

Onyx marbles (using the term in the sense above mentioned) differ from marbles of the common type only in that they are purely chemical deposits rather than products of metamorphism from pre-existing calcareous sediments. The travertine varieties are probably products of deposition from hot springs carrying lime carbonate in solution, together with small quantities of iron and manganese carbonates and other more rarely encountered constituents. The stalactite and stalagmite varieties differ only in manner of formation, being cold-water depositions made on the roofs, walls, and floors of limestone caves. Both varieties owe their banded structure and variegated colors to the intermittent character of the deposition and the varying content of impurities like the metallic oxides.

The onyx marbles are considered the most beautiful of decorative stones, they cut readily and take a high finish, and are largely used for interior decorations.

A large part of the onyx marble used in the United States is imported from Mexico. There are, however, important quarries in Arizona, California, and Virginia. The foreign onyx comes largely from Algeria and Italy.

222. Sandstones. " Sandstones are composed of rounded and angular grains of sand so cemented and compacted as to form a solid rock. The cementing material may be either silica, carbonate of lime, an iron oxide, or clayey matter." *

Sandstones vary greatly in color, hardness, and durability, but include many of the most valuable varieties of building stone for exterior construction. The qualities of sandstones as a structural material depend

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* Merrill, " Stones for Building and Decoration," p. 299.

largely upon the character of the cementing material, the character of the sand grains being very nearly the same for all, i.e., a pure quartz. If the cement is silicious the stone is light colored, hard, and sometimes difficult to work, but very durable. If iron oxides comprise the greater part of the cementing material, the color is a red or brownish tone and the stone usually is not too hard to work well, though it does not always prove very durable. If the cementing material is lime carbonate the stone is light colored, soft, and easy to work, but less durable than either of the above varieties. Clayey sandstones are the poorest class. They are soft and easily cut, but are particularly subject to the disintegration caused by weathering because of their high absorption. Some sandstones contain very little cementing material, but owe their strength largely to the pressure under which they have been solidified. Such stones are a light gray color, work easily, and if they possess sufficient cohesive strength, are very durable. A few sandstones contain varying amounts of grains of feldspar or mica, in which case they are inferior to ones the grains of which are entirely quartz. The following are the principal well-known sandstones in this country:

The brownstones of Connecticut, Massachusetts, Pennsylvania, New Jersey, North Carolina, and a few other localities, are handsome dark reddish-brown stones, fine grained, easy to work, and capable of taking a good "rubbed" finish. With the exception of the Massachusetts stone, they occur in distinctly laminated beds and must be used on their natural beds. These stones, having iron oxides for a great part of their cementing material, are usually subject to the disintegrating effect of atmospheric agencies and therefore do not usually rank especially high in durability, but have been largely used in all the large eastern cities.

The *Ohio stone*, *Berea sandstone*, or *Amherst stone* is a fine-grained light buff, gray, or blue-gray stone having silica for the most part as its cementing material, the amount of cement being low. These stones cut and work readily, are well adapted to carving, and, when those portions containing iron pyrites are excluded, are very durable. The principal quarries are located at Amherst, and at Berea, Ohio, and the stone has been largely used in the cities of the middle West.

The *Waverly stone* is a fine-grained homogeneous stone of a light drab or dove color, quarried only in the vicinity of Cincinnati, Ohio. It is sometimes called the *Euclid bluestone*. It resembles the Ohio stone except that it has a finer and more compact texture. It works easily and, except for portions containing iron sulphides, is a handsome and durable stone.

The *Potsdam red sandstone* from Potsdam, New York, is composed wholly of quartz grains cemented by a small amount of silica with just enough iron oxide to give it a reddish or brownish-red color. It is fine-grained, handsome in appearance, works well though rather hard, and is the strongest and most durable of sandstones after becoming hardened by seasoning. Its composition being practically quartzite, it is as strong as granite, and particularly non-absorptive, making it practically proof against all disintegrating influences.

The *Lake Superior stone* is a Potsdam stone of medium fineness. It has a light red-brown color and is often spotted gray. It is quarried largely at Marquette, Michigan. This stone resembles the Potsdam stone of New York except that it has rather more cementing material and therefore is not quite as hard and strong. It works well and is very durable. Its use has been principally limited to Michigan cities.

The *Medina sandstone* of Western New York is a hard moderately fine-grained stone, either red or gray in color. The red variety resembles the Potsdam stone, except that it is not so fine in texture, and is similarly used. The gray variety is rather too hard to work for general building purposes, but is largely used for street paving and curbing, where it has the advantage of some other hard stones, like granite or trap, in that it does not wear smooth.

The *Rocky Mountain sandstones* include many varieties of excellent building stone. The best-known ones are very fine-grained, soft-textured stones of a dark-brown color. They work well, take a good " rubbed " finish, and are fairly durable.

223. Slates. Slates perhaps may not properly be considered as building stones, but their extensive use as roofing material and for various interior building uses classes them as a building material.

Ordinary slate is a siliceous clay, compacted and more or less metamorphosed after deposition as fine silt on ancient sea bottoms. The pressure due to thousands of feet of overlying material is largely responsible for the solidification of the clay into rock having very marked cleavage planes. The most valuable characteristic of slate is its pronounced tendency to split into thin sheets having smooth regular surfaces. The non-absorptiveness of slate, its great toughness and mechanical strength and its non-conductiveness for electric currents, are other valuable attributes. Slate must be split while fresh from the quarry, and the quarry loss amounts to more than 50 per cent of the rock.

PHYSICAL AND MECHANICAL PROPERTIES OF BUILDING STONES

224. Selection of Building Stone. The selection of a proper stone for construction purposes is dependent to a great extent upon the climate where the stone is to be used. The range of changes of temperature, the average humidity of the atmosphere, the possibility of acid fumes in the atmosphere of many cities, and the possibility of the stone being subjected to high temperatures by fire, are among the considerations which must be carefully taken into account. Very often the only considerations given weight by an architect are the cost and the appearance. He is very apt to take great care to secure a color which harmonizes with the general scheme of the structure on which it is used, but wholly overlook the question of whether the stone chosen possesses satisfactory weathering qualities.

The actual mechanical strength of stone is seldom of great importance because of the fact that stones in masonry structures can never be loaded to their full capacity because of the comparative weakness of the mortar joints.

225. Properties of Various Stones. *Durability.* The durability of stones depends upon ability to withstand weathering agencies, and the structure, texture, and mineral composition are the real determining factors. Joint planes, cracks, or other structural imperfections afford an opportunity for water to enter and for disintegration to begin through frost action. Stones of coarse-grained texture are more subject to the disintegrating influence of temperature changes than fine-grained ones, and dense stones, owing to their practical imperviousness, are less apt to be injured through frost action than are porous ones. Of the mineral compounds which make up our common rocks sulphides are among the least resistant to weathering agencies, iron compounds in general are undesirable in large quantities, calcium and magnesium carbonates weather rather rapidly, aluminates weather less rapidly, and silicates or silica are most resistant to decay. The fact must not be overlooked in this connection that the three factors, structure, texture and mineral composition, are simultaneously operative so that a very dense fine-grained stone made up principally of carbonate may weather well, while a porous or structurally imperfect stone made up principally of silica may weather poorly.

The estimated life of various building stones is indicated by the following table quoted by Ries and Watson * from the observations made by A. A. Julian in New York City.

Kind of Stone.	Life in Years.
Coarse brownstone	5 to 15
Fine laminated brownstone	20 to 50
Compact brownstone	100 to 200
Bluestone (sandstone) untried,	Perhaps centuries
Coarse fossiliferous limestone	20 to 40
Fine oolitic (French) limestone	30 to 40
Marble, coarse, dolomitic	40
Marble, fine, dolomitic	60 to 80
Marble, fine	50 to 100
Granite	75 to 200
Gneiss	50 years to many centuries

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* "Engineering Geology," p. 432.

Absorption. The absorption or absorptive power of stones is represented by the weight of water that can be absorbed expressed as a percentage of the dry weight of the stone. Absorption is directly dependent upon the porosity of stones, though this relation is not necessarily any fixed ratio. The gain and loss of moisture when a stone is first exposed in a damp or wet situation and then dried, will be most rapid if the pores are large or straight, and least rapid if they be small or tortuous. The following figures constitute an abstract from the results of absorption tests made by Hirschwald.* The lower values are those found when submersion was rapid, the higher values when submersion was slow. No pressures above atmospheric pressure were used in these tests.

	Percentage Absorption.	Percentage of Pore Volume.
Sandstone	4.89- 7.33	52.97-64.88
Marble	0.36- 0.49	59.47-84.27
Limestone	7.51- 7.88	35.45-37.20
Slate	0.51- 0.55	72.92-79.16
Tuff	22.11-23.41	65.51-69.71
Granite	0.51- 0.91	41.20-57.71

It appears from these tests that the absorption of igneous and metamorphic rocks rarely exceeds ½ of 1 per cent. (The tuff is a very porous volcanic rock which is not used as a building stone and hence may be disregarded.) The sandstones absorb at least ten times as much as granites, marble, and slate, and the limestones absorb even more moisture than the sandstone.

Expansion and Contraction. Stones, like most other materials, expand upon being heated and contract when cooled. Unlike most other materials, however, they do not quite return to their original volume when cooled after heating, but show a swelling which is permanent. Experiments made at the Watertown Arsenal † by heating from 32° to 212° F. and cooling through the same range, showed the following amount of permanent increase in length for the various stones tested:

PERCENTAGE PERMANENT INCREASE IN LENGTH

	Min.	Max.	Ave.
Granites	0.0085	0.0355	0.0200
Sandstones	0.0015	0.0870	0.0235
Limestones	0.0120	0.0595	0.0350
Marbles	0.0145	0.0980	0.0450

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* Hirschwald, "Handbuch der Bautechnischen Gesteinsprüfung."

† "Tests of Metals," 1895, p. 322.

The coefficient of temperature expansion per degree Fahrenheit for various building stones was found in a series of tests at the Watertown Arsenal * to be very variable, the range of values found being as follows: Granites, 0.00000311 to 0.00000408; limestones 0.00000375 to 0.00000376; marbles 0.00000361 to 0.00000562; sandstones 0.00000501 to 0.00000622.

Frost Resistance. Stones can be disintegrated by frost action only when the pores are practically filled with water before exposure to freezing temperatures. As stones seldom are used under such conditions that the maximum amount of water is absorbed, instances of injury to good building stones by frost action are very rare. Experimental work on the resistance of stones to disintegration by frost indicates that the pores can be filled with water, so that the subsequent expansion upon freezing will cause rupture, only by the use of high pressure or by first exhausting the air by a vacuum. It will be apparent therefore that only stone of the greatest absorptive power combined with low structural strength can ever be injured by frost action under the conditions encountered in practice.

Fire Resistance. Practically all building stones are seriously injured if exposed to such high temperatures as may be encountered in case of fires, and particularly so if exposed to the combined action of fire and water. The cause of disintegration is usually explained to be the internal stresses caused by unequal expansion of unequally heated portions of the material. This explanation is rendered more forcible by the observed fact that if highly heated stones be suddenly cooled on the exterior by application of water, the resultant disintegrating action is much more pronounced than when the cooling is slow. The texture of the stone, and the relative coefficients of expansion of its individual mineral constituents probably are also factors of importance.

Experience has shown that granites are particularly poor fire resistants. Probably on account of the irregularity of the structure and the complexity of the mineral composition, granites crack irregularly and spall badly. The coarse-grained granites are most susceptible to the action of fire and water, and the gneisses often suffer even more severely because of their banded structure.

Limestones suffer little from heat until a temperature something over 600° C. is reached, at which point the decomposition of the stone begins, owing to the driving off of carbon dioxide. The stone then has a tendency to crumble due to the flaking of the quicklime formed. Curiously enough the limestones do not suffer so much by sudden cooling as by a slow cooling.

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* "Tests of Metals," 1890, p. 1108.

Marbles, owing to the coarseness of the texture and the purity of the material, suffer more than limestones at temperatures below the point where calcination begins. The cracking is irregular and the surface spalls off as in the case of granites.

Sandstones, especially if of a dense, non-porous structure, suffer from high temperatures and sudden cooling less than most other building stones. (We except limestones which are good fire-resistants only below the temperature of calcination.) The cracking of sandstones which does occur, appears mostly in the planes of the laminations, which should be horizontal planes as the stone is set. These cracks are therefore not as serious as irregular cracks. Sandstones whose cementing ingredient is silica or lime carbonate are better fire resistants than ones whose grains are bound by iron oxide or clay.

Mechanical Properties of Stones. The following tabulation of mechanical properties of the principal classes of building stone has been compiled from the Watertown Arsenal Tests * of 1894 and 1895 to serve as an approximate guide in the selection of a building stone.

It will be noted by reference to the table that the properties of the different varieties of building stones of the same general class vary greatly. It is, therefore, not advisable to use the average strength indicated except in a very general way, the safe working stress being determined by the use of a large factor of safety. (Taken at from 15 to 35, depending upon the structural use made of the stone, and the amount of variation shown in tests of the particular variety of stone used.) For all situations involving high stresses, as in the case of monolithic columns in buildings, the stone should be chosen only after tests have been made of the particular stones under consideration.

STONE MASONRY

226. Classification.† All stone masonry is classed as *rubble masonry*, *squared stone masonry*, or *ashlar* or *cut-stone masonry*. " Rubble masonry includes all stone masonry composed of unsquared stones. It may be *uncoursed rubble*, Fig. 125*a*, laid without any attempt at regular courses, or *coursed rubble*, Fig. 125*b*, leveled off at specified heights to a horizontal plane.

Squared Stone Masonry. " According to the character of the face, this is classified as *quarry-faced*, Fig. 125*c*, or as *pitch-faced*, Fig. 125*d*. If laid in regular courses of about the same rise throughout, it is *range work*, Fig. 125*e*. If laid in courses that are not continuous throughout

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* "Tests of Metals," 1894, 1895.

† Trans. Am. Soc. C.E., Vol. 6.

MECHANICAL PROPERTIES OF BUILDING STONES

Name. Locality.	Comp. Strength. Lbs. per Sq.in.	Mod. of Rupture. Lbs. per Sq.in.	Shearing Strength. Lbs. per Sq.in.	Weight, Lbs. per Cu.ft.	Mod. of Elas., Lbs. per Sq.in.
GRANITE:					
Little Rock, Ark	21,559	1520	2205	156.2	7,040,000
Millbridge, Me	19,917	2048	2820	....	9,800,000
Chesterfield, Va	15,350	1672	2065		
Korah, Va	23,446	1608	2662		
Exter, Cal	22,557	1853	2419		
Rockville, Minn	18,121	1327	1949	....	9,420,000
Sioux Falls, Minn	18,176	1216	2086	....	6,010,000
Troy, N. H	26,174	2169	2214	164.7	
Branford, Conn	15,707	1249	1834	161.6	6,997,000
Milford, Mass	21,235	1545	2311	162.6	5,927,000
Average	20,224	1630	2257	161.3	7,532,000
MARBLE:					
(White) Rutland, Vt	11,892	1247	1023	167.6	4,455,000
(Blue) Rutland, Vt	13,864	2057	1217	....	7,267,000
(Dark) Rutland, Vt	12,833	1759	1453	....	9,290,000
Sutherland Falls, Vt	16,156	2293	1565	....	12,580,000
(Fossil) St. Joe, Ark	10,312	1615	......	....	8,210,000
(Brown), St. Joe, Ark	12,278	1614	......	....	10,740,000
(White) De Kalb, N. Y	12,497	839	......	....	12,000,000
Marble Hill, Ga	11,505	1038	1332	167.8	5,515,000
Tate, Ga	12,425	1079	1315	168.7	4,020,000
Average	12,640	1505	1318	168.0	8,231,000
LIMESTONE:					
La Motte, Vt	14,622	1640	2173	....	14,720,000
Dodge Co., Minn	4,522	253	1135	....	
Junction Cy., Kan	3,173				
Fort Riley, Kan	......	528	1022		
Beaver, Ark	20,581	2707	1998	....	6,645,000
Mt. Vernon, Ky	7,647	1314	1705	139.1	4,000,000
Rockwood, Ala	5,957	690	978		
Bowling Gr., Ky	6,043	1058	1211	....	9,290,000
Bedford, Ind	9,918	1736	1119	....	7,160,000
Average	9,058	1241	1418	139.1	8,363,000
SANDSTONE:					
Cromwell, Conn	16,894	1872	1526	....	7,711,000
E. Long Mead., Mass	10,004	941	1199	133.8	1,582,000
Jasper, Ala	15,630	1889	2202	....	
Pike Co., Minn	12,547	868	1555		
Cabin Creek, Ark	18,468	1666	2479	....	3,900,000
Fort Smith, Ark	12,765	1473	1765	....	3,530,000
Redfield, Kan	8,027	2088	1940	....	
Oakland, Cal	11,041	1063	1626		
Coos Co., Ore	7,444	......	1248		
Olympia, Wash	12,655	2185	1643	....	3,277,000
Chuckanut, Wash	11,533	1488	1809	....	2,120,000
Tenino, Wash	6,688	495	1226	....	1,020,000
Pittsburg, Wash	19,208				
Average	12,531	1457	1685	133.8	3,306,000

the length of the wall, it is *broken range* work, Fig. 125*f*. If not laid in courses at all, it is *random* work, Fig. 125*g*."

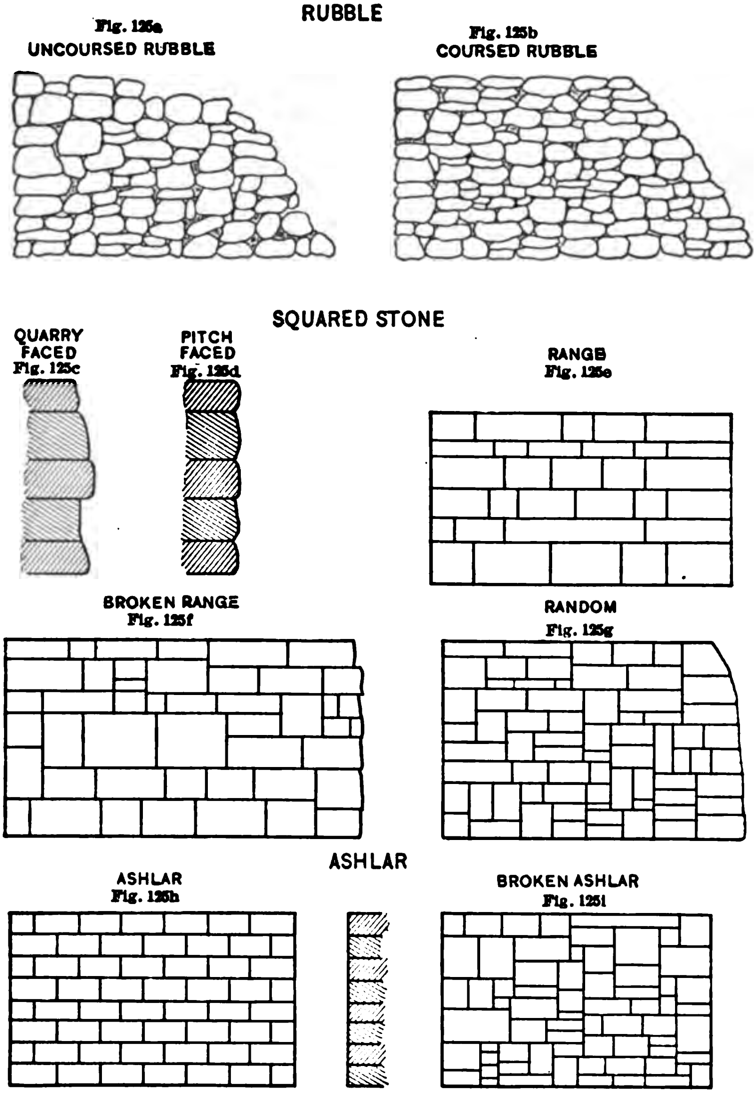

Fig. 125.—Stone Masonry.

Ashlar Masonry. "This is equivalent to cut-stone masonry, or masonry composed of any of the various kinds of cut stone mentioned above."

As a rule the courses are continuous, Fig. 125*h*, but sometimes are broken by the introduction of smaller stones of the same kind and then it is called *broken ashlar*, Fig. 125*i*.

227. Compressive Strength. The actual compressive strength of stone masonry has not been satisfactorily determined experimentally. The few tests which have been made do not form a sufficient basis for the determination of the relative strengths of the different classes of masonry, nor the relative strengths of masonry of the same class when different kinds of stone are used. The following data are abstracted from the report upon a limited series of tests made by the Austrian Society of Engineers and Architects in 1898–1901.

COMPRESSIVE STRENGTH OF MASONRY PIERS

Compressive Strength, Single Stone. Lbs. per Sq.in.	Compressive Strength, Masonry Piers.		Ratio of Strength of Masonry to Strength of Stone.	
	1 : 2 Mortar Lbs. per Sq.in.	1 : 3½ Mortar, Lbs. per Sq.in.	1 : 2 Mortar, Lbs. per Sq.in.	1 : 3½ Mortar, Lbs. per Sq.in.
10,380	3220	2730	33.6%	28.5%
8,780	3870	2820	40.4	29.4
Ave. 9,580	3545	2775	37.0	29.0

The piers tested with the above results were built of hard sandstone blocks about 6 inches thick, and either about 12 by 20 inches, or 7 by 9 inches, in transverse dimensions. The stones were laid with either 1 : 2 or 1 : 3½ Portland cement mortar, joints ½ to ¾ inch thick, the vertical joints being broken. The whole constituted a pier about 40 inches high, with a 20 by 20-inch base, having six courses and seven mortar beds.

There is no opportunity afforded by these tests to compare the relative strength of masonry with stones of different strength or with different kinds of mortar other than the two mixes of Portland cement mortar. It is evident that the strength of any masonry will be largely dependent upon the mortar used, and it is also a fact that the masonry will be strongest when the joints are thinnest.

An analogy may perhaps be considered to exist between the relative strength of stone masonry and the stone employed therein, and the relative strength of brick masonry and the brick employed therein. Experimental data to fix the latter point are by no means lacking, since comprehensive series of tests have been conducted in several different laboratories.

A series of tests conducted at the Watertown Arsenal in 1904 has been used to abstract the following data: Tests of six classes of brick have been selected, including tests of dry-pressed face brick, repressed mud brick, wire-cut mud brick, hard sand-struck brick, and light hard sand-struck brick. These bricks were tested singly in compression, and in piers built with a 12 by 12-inch base, 8 feet high. The mortars used were neat Portland cement; 1 : 3 Portland cement mortar, and 1 : 3 lime mortar. In spite of the wide variation in the strength of the different classes of brick used, the variation in the ratio of the strength of the masonry to the strength of the brick was only within narrow limits for each class of mortar used. For neat cement the ratio varied from about 23 per cent to about 28 per cent, averaging about 26 per cent; for 1 : 3 cement mortar the ratio varied from 19 per cent to about 28 per cent, averaging about 24 per cent; while for the 1 : 3 lime mortar the ratio varied from about 10 per cent to about 18 per cent, averaging about 13 per cent.

It would appear then that the strength of stone masonry, if the above-mentioned analogy holds, is dependent almost entirely upon the strength of the mortar joints, the actual strength of the stone not being a great factor except with the strongest mortars laid with the thinnest joints.

The manner of failure of masonry under compression is almost invariably by the compressive failure of the mortar, followed by lateral flow of the latter, thus setting up tensile stresses in the stone which open up longitudinal cracks. Actual compressive failure of the stone in masonry is very rare indeed.

228. Allowable Loads on Stone Masonry. The building laws of the city of Chicago recommend the following values as safe pressures for the different classes of stone masonry:

ALLOWABLE LOADS ON STONE MASONRY

Kind of Masonry.	Pounds Sq. in.
Rubble, uncoursed, in lime mortar	60
Rubble, uncoursed, in Portland cement mortar	100
Rubble, coursed, in lime mortar	120
Rubble, coursed, in Portland cement mortar	200
Ashlar, limestone, in Portland cement mortar	400
Ashlar, granite, in Portland cement mortar	600

CHAPTER X

BRICKS AND OTHER CLAY PRODUCTS

GENERAL

229. Clay Products as Structural Materials. The principal clay products used structurally are building brick, paving brick, fire brick, terra cottas, and various forms of tiles. Brick has been used since the earliest times as a masonry material. Brick masonry possesses the great advantage of being exceedingly strong and durable, cheap as compared with stone masonry, and, owing to their artificial character, a wide latitude is possible in size, form, color, and structural character of the bricks themselves.

Brick may be made from a large number of different classes of material, the one essential being that the material be of a mineral nature and possess a considerable degree of plasticity when dampened. Common building bricks are usually made of a mixture of clay and sand (to which coal and other foreign substances are sometimes added), which is mixed and molded in various ways, after which it is dried and burnt.

Paving bricks are made primarily as a material for street pavements. Certain classes of paving bricks are largely used, however, as a substitute for building brick.

Fire bricks are of such a nature that they will withstand high temperatures. Their structural uses are largely confined to linings of flues, stacks, etc.

Terra cotta is made of selected clays in much the same way as ordinary brick. The architectural terra cotta is much used for decorative effect on building interiors and exteriors, and terra cotta lumber and hollow blocks are much used for both interior and exterior walls of buildings and as fireproofing to protect steel-work.

Tiles, made by burning various classes of clay are used in various forms as roofing tile, wall or floor tiles, drain tiles, sewer pipe, etc.

230. General Classification of Bricks and Clay Products. The principal classes of bricks and other clay products which are used as building materials, are included in the following classified list, in which certain subdivisions of the materials above mentioned have been made:

- (1) Building bricks.
    - (*a*) Common building brick.
    - (*b*) Face, or pressed brick.
    - (*c*) Enameled or glazed brick.
    - (*d*) Ornamental brick, tapestry brick, and Roman tile.
    - (*e*) Hollow brick.
    - (*f*) Sand-lime brick (not a clay product).
- (2) Paving bricks.
- (3) Fire bricks.
- (4) Terra cotta.
    - (*a*) Architectural.
    - (*b*) Terra-cotta lumber.
    - (*c*) Hollow building blocks and fireproofing.
- (5) Roofing, wall, and floor tiles.
- (6) Drain tile and sewer pipe.

The manufacture, properties, and uses of each of these classes of building material will be briefly discussed in the paragraphs which follow.

MANUFACTURE OF BUILDING BRICKS

231. Kinds of Clay. Their Use in Brick Making. The different classes of clay from the standpoint of geological manner of formation have been discussed above in Art. 83. Of the three general classes, residual clays, sedimentary clays, and glacial clays, only the sedimentary clays possess a sufficient fineness, homogeneity and plasticity to be suitable for use in brick making. The following classification of sedimentary clays is made by Ries: *

CLASSIFICATION OF SEDIMENTARY CLAYS.

- (*a*) *Marine clays or shales* (deposits often of great extent).
    - White-burning clays. Ball clays and plastic kaolins.
    - Fire clays or shales, buff burning.
    - Impure clays or shales.
        - (1) Calcareous.
        - (2) Non-calcareous.

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* Dr. Heinrich Ries, "Economic Geology," p. 128.

(b) *Lacustrine clays* (deposited in lakes or swamps).
  Fire clays or shales.
  Impure clays or shales, red-burning.
  Calcareous clays, usually of surface character.
(c) *Flood-plain clays* (usually impure and sandy).
(d) *Estuarine clays* (deposited in estuaries, mostly impure and finely laminated).

Marine deposits of clay often stretch for hundreds of miles with a depth of 30 feet or more. Their composition is remarkably uniform, they are free from fossils and, except in the case of those which are too high limed or are excessively plastic, form the best clays obtainable for brick manufacture.

Lacustrine clays occur in beds of limited extent and usually of no great depth. Pebbles and fossils are apt to be present and the clays are less advantageous for use in brick-making than are the marine clays.

Flood-plain clays and estuarine clays are even more apt to be contaminated than are lacustrine clays, and therefore cannot usually be advantageously used.

232. Influence of Kind of Clay upon Character of the Brick. Most clays used in brick making contain in addition to silicate of alumina, small quantities of lime, magnesia, and iron oxide. If the clay is too high in alumina it will be very plastic, but will shrink, crack, and warp in drying and be very hard after burning. The presence of silica in amounts not exceeding 25 per cent tends to prevent shrinking and cracking and allows partial vitrification. An excess of silica in the shape of sand destroys cohesiveness, however. Iron oxide acts as a flux and adds greatly to the hardness and strength of brick. It causes the clay to burn buff or red in color according to the amount of iron oxide present. Lime, if present not in excess, acts as a flux and also decreases shrinkage. In excess it causes brick to soften and deform excessively in burning. The lime must be in a very finely divided state so that it will be completely hydrated in the process of manufacture of the brick. The presence of lumps of unhydrated lime which become hydrated after long periods is the cause of unsightly defects on brick walls called "lime-pops."

Magnesia in small amounts acts as a flux and decreases shrinkage.

HAND PROCESSES OF MANUFACTURE

233. Preparation of the Clay. A considerable proportion of the common brick made and used, apart from the large cities, is still made by hand, and many specially molded brick made for various special purposes are made by hand methods.

The clay must first be freed from any pebbles, soil, excessive sand, etc., by washing. This is usually done in a wash mill similar to those described in connection with the wet process of cement manufacture. With the better class of clays this step is not required.

Clays not put through a wash mill sometimes require crushing to reduce them to a state in which they readily mix with water. This is usually accomplished in either a set of rolls or in a wet edge-runner mill such as has been described above. Clays which require an excessive amount of crushing are not usually used in hand processes.

After crushing, the clay is tempered by mixing in a moderate amount of water and then turning it by hand and allowing it to stand for a time before the final pugging of the mix.

234. Pugging. The final reduction of the mix to a plastic mass is done in a pug-mill. At this stage it may be necessary to add sand, chalk, or other non-plastic material, and more water, the exact proportions being carefully controlled and kept uniform.

The pug-mill, Fig. 57, is usually a horizontal cylinder provided with one or two power-driven blades. The revolving blades slice up and mix the mass till it is ejected through an opening at one end.

235. Molding. There are two common methods of hand-molding. In the first, known as *slop-molding*, the mold is dipped in water just before filling to prevent the adhesion of the clay to the metal. The workman kneads the clay into approximate shape with his hands, forces it into the mold and tamps it hard, and then strikes it even with the mold by the use of a straight-edge. The mold is not removed till the brick reaches the dryer room. This method is slow and yields many imperfectly formed bricks. The second method is called *sand-molding*, and differs from the first in that, instead of dipping the molds in water to prevent the clay from sticking, the mold is sprinkled with sand to effect the same purpose. The operation of filling the mold is practically the same as in the first method, but, owing to differences in the details of manipulation, the second method is more rapid and the bricks are usually cleaner and sharper than those produced by slop-molding. The latter method is now seldom used.

236. Drying. After being shaped in the mold the bricks are allowed to dry for several weeks before being fired. Artificial dryers are seldom used in connection with hand processes. Very often the drying is accomplished in the open air on racks which support the brick in such a manner as to allow a maximum access of air and sunlight to all sides of the tiers of brick. In order to prevent injury by rain it is desirable to cover the tiers with a light roofing of boards. For the better qualities of bricks sheds containing racks must be used, or an artificial dryer installed. These sheds are permanent structures provided with a weather-tight roof, and with side walls which are either fitted with shutters or which are built of perforated bricks. Drying requires a length of time which is dependent upon the amount of water contained in the brick. Soft-mud brick and slop-molded brick often require from three to six weeks drying; stiff-mud brick and sand-molded brick are sometimes fired after less than one week on the drying racks.

237. Pressing. When hand-made brick are to be pressed the drying must be carefully watched and they must be taken to the press before becoming too dry and hard. The press used is a portable one which is operated by hand. The bricks are placed one by one in the machine between dies and compressed by a piston operated by a lever. The bricks are pressed and replaced on the rack as fast as they can be handled, the press being wheeled along between the racks as the work proceeds.

The kilns used in hand processes differ in no respect from those used for machine-made brick (Art. 242), except that the more elaborate types of kilns and especially the continuous kilns are seldom used in connection with hand molding.

Machine Processes

238. General. Brick-making upon a large scale is now done almost entirely by machinery, from the mining of the clay by steam shovel to the molding in automatic machines and burning in semi-automatic kilns. The equipment used for the manufacture of machine-made brick varies greatly, on account of variations in the character of the raw material available, and variations in the class and quality of brick desired.

There are three general processes employed in brick manufacture, viz.: *The soft-mud process*, the *stiff-mud process*, and the *semi-dry process*. These processes must be separately considered.

239. Soft-mud Process. *Preparation of the Clay.* The soft-mud process is practically the same as that employed in hand processes except that hand work is largely replaced by machines. The clay, unless it is found very free from pebbles and excess sand, is first cleaned in a wash-mill, after which it is tempered, coal dust or sand being added, if desired, in the tempering tanks, and then pugged in the machine which fills the molds.

Molding and Drying. The upper part of the molding machine is virtually a pug-mill which delivers the pugged mass to molds below where it is pressed into place by a plunger. The filled mold is now moved to one side and a second mold is brought into place and filled while the brick last made is being removed from its mold. The amount of pressure exerted on the clay is necessarily under constant control since variations in the stiffness of the clay make variations in pressure necessary. The machine generally uses gang-molds and so makes perhaps four or six bricks at each stroke of the plunger. The molds are usually sanded by hand between reversals of the table which shifts the molds back and forth under the plunger. The capacity of a machine is about 8000 to 10,000 bricks per day, which is about twice or three times the speed of hand-molding of sand-struck brick, and five or six times the speed possible in the molding of slop-brick by hand.

The drying of the soft-mud machine-made brick is often accomplished in the same manner as has been described above, referring to hand-made brick. In some instances artificial drying is resorted to, the equipment being that described below.

240. Stiff-mud Process. *Preparation of the Clay.* The making of brick by the above-described methods means the incorporation in every brick of a pound or more of water which must later be dried out and driven off in the kiln. A process whereby the brick clay is only sufficiently moist to possess the requisite coherency under moderate pressure results therefore in economy of time in drying, and economy of fuel in burning.

This process requires in the first instance a clay which is not too wet. The lumps are broken up without the addition of water in a pug-mill or mixer which resembles the one above described. The clay is now finely disintegrated in an edge runner mill (Fig. 56), after which it is pugged with or without the addition of water, either in a separate pug-mill or in the brick-making machine itself.

Molding. The brick-making machine may be either of two general types, viz., the *auger type* (Fig. 126) or the *plunger type* (Fig. 127). The auger machine consists of a closed tube of cylindrical or conical shape, in which, on the line of the axis of the tube, revolves a shaft to which is attached the auger and auger knives. The knives are so arranged as to cut and pug the clay and force it forward into the auger. The function of the auger is to compress and shape the clay and force it through the die. When the clay passes through the die it is compressed to as great an extent as it can be in its semi-plastic condition. The opening in the die is made to conform to the dimensions of either the end or the side of a brick, and a continuous bar of clay is forced through onto a long table where it is cut into sections the size of a brick. If the cross-section of the bar is the same as the end of the brick the brick are called *end-cut*, and when the section corresponds to the side of a brick they are *side-cut.* When end-cut brick are made the clay often issues from the machine in several separate streams.

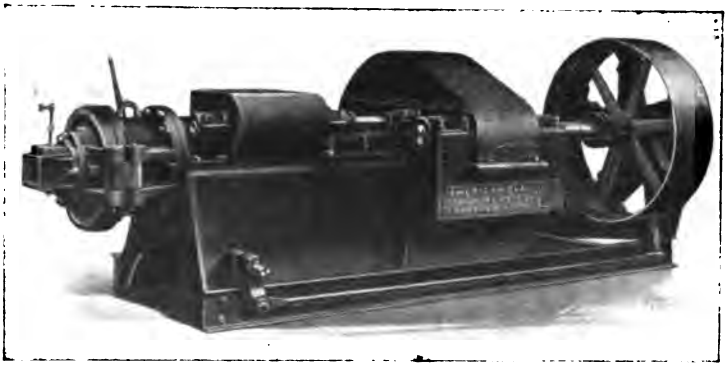

FIG. 126.—Auger Type Brick Machine.

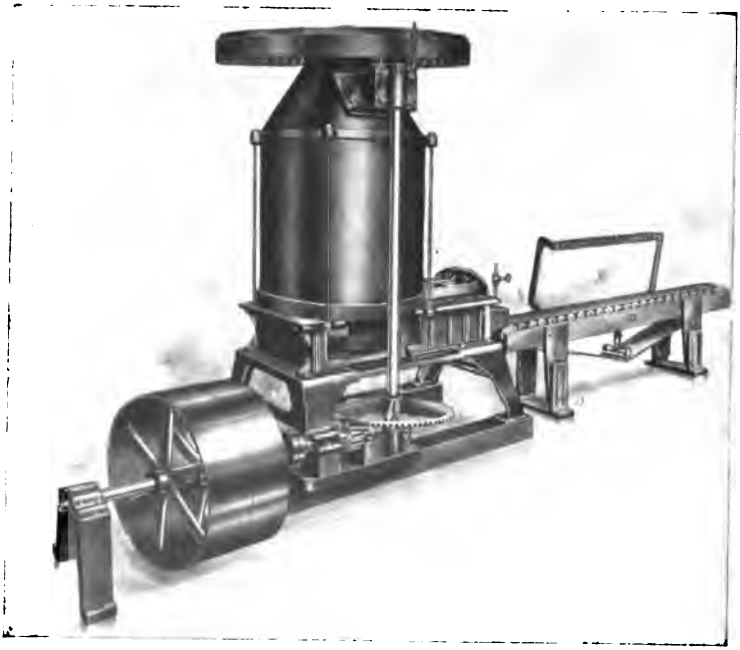

FIG. 127.—Plunger Type of Brick Machine with Wire-cutting Table.

One of the commonest types of cutting table is shown in Fig. 127. The bar of clay as it issues from the die travels along the table on an endless belt which is supported on rollers. At intervals the operator throws a lever which swings downward a rigid frame across which a series of wires are tautly stretched. Thus the bar is cut into sections of either the length or the thickness of a brick. When the lever is reversed the wire frame is restored to a vertical position and the cut brick are carried away on a belt conveyor. Many types of machines are used for cutting the bar of clay into bricks, but all use wires to do the actual cutting.

The great majority of bricks made by the stiff-mud process are made in the auger type of machine. The plunger type of machine is used to some extent, however.

In the plunger type of machine (Fig. 127) the clay after pugging is forced into a closed chamber which acts as a feeder for the pressure cylinder into which it discharges, the amount discharged being subject to control. The forward motion of the plunger now compresses the clay and forces it through the die. The clay bar thus formed passes onto the cutting table and is cut by wires in the manner above described.

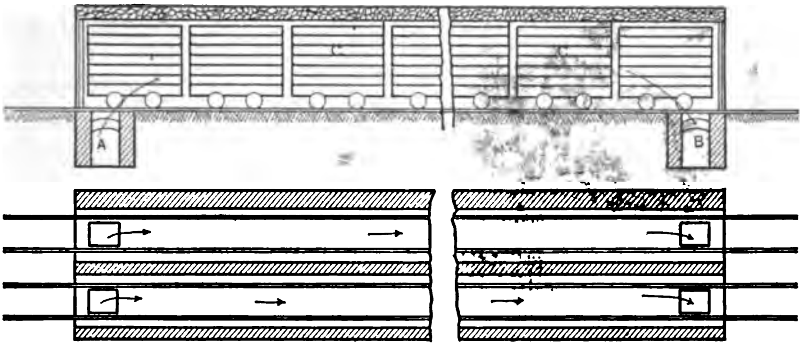

FIG. 128.—Tunnel Dryer.

A few plunger machines are so devised that the clay is forced into molds instead of through a die. With this exception, all stiff-mud brick are *wire-cut brick*.

Drying and Pressing. Many manufacturers of stiff-mud brick burn the brick without any intermediate drying. The practice is not a good one, however, since it is apt to cause excessive warping and cracking of the brick unless the firing is done with great care and very slowly. The average stiff-mud brick is improved by a moderate amount of drying before burning. The drying racks or dry-houses above described are sometimes used, but, since the bricks contain much less moisture and are stronger, the drying may be accelerated and artificial heat used.

The continuous tunnel dryer (Fig. 128) is most commonly used for rapid drying of green bricks. The bricks are piled on cars which move slowly through tunnels wherein they are heated either by hot air or by steam pipes. The tunnels are usually built of masonry, are 100 feet or more in length, and the cars traverse the length of the tunnel in about twenty-four hours.

Fig. 129.—Brick Re-pressing Machine.

The usual product of the stiff-mud brick machine may be sorted into a small proportion of the face brick and a large proportion of common brick. When, however, a special face-brick is desired, the brick may be repressed in a mold under a plunger worked by a steam cylinder. Fig. 129 shows a common type of repressing machine. Repressing reshapes the brick, rounds the corners if desired, trues it in outline, and improves its appearance. Well made stiff-mud brick are apt to be structurally injured and weakened by repressing.

241. Dry-clay Process. *Preparation of the Clay.* The dry-clay process is especially fitted for the handling of clays which contain not over about 7 per cent moisture when they come from the bank. The clay is quarried by steam shovel and stored under cover to allow further drying, ground up in a dry pan (edge-runner), delivered to a mixer, which is simply an open pug-mill, in which it is thoroughly mixed to give a homogeneous product of about the consistency of flour, and discharged into the hopper of the brick machine.

Molding. The molding of dry-clay brick is a difficult operation, the success of which is largely dependent upon the efficiency of the brick machine used. The type of machine illustrated (Fig. 130) is one of the most satisfactory ones in general use. In this machine the clay is fed into the die or molds by a reciprocating charger located below the machine hopper. At each revolution of the machine the charger moves forward, and when it is directly over the molds the bottom plunger in the molds descends, allowing the molds to be filled with clay. The charger is withdrawn, the clay supply shut off, and the top and bottom plungers move toward each other in the molds, compressing the clay between them. The pressure is now relieved and then applied a second time, the compression of the clay being carried a bit further than in the first place. The upper plunger is now withdrawn and the bottom plunger raises the brick to the level of the top of the mold. The next stroke of the plunger pushes the finished brick upon the mold table, whence it is removed to the dryers or kilns. Many machines used with dry clay are arranged to mold two, four, or more bricks at each stroke.

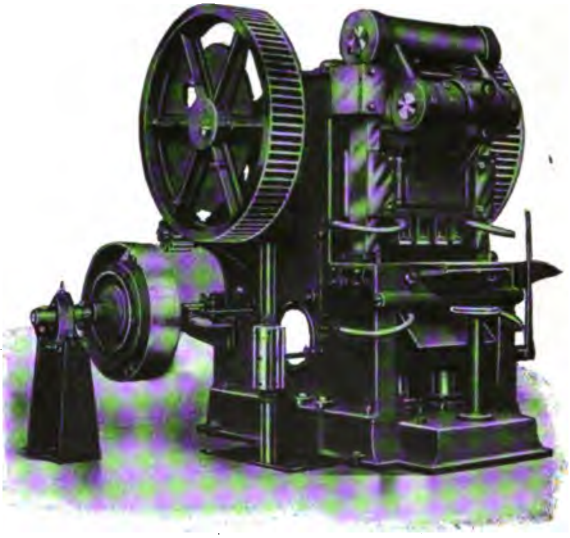
Fig. 130.—Dry Clay Brick Machine.

Dry-pressed bricks are very compact, show high compressive strength, and are well formed, but they are not generally considered to be as durable as bricks the clay for which has been tempered. They are, however, largely used as face brick. The term " pressed brick " is properly used only in referring to bricks made by the dry-clay process. The so-called pressed brick made by repressing of soft or stiff-mud brick should be called " repressed brick."

Building bricks are occasionally made by a process called the *semi-dry clay process.* It differs little in methods or equipment used from the dry-clay process.

242. Kilns and Burning. Brick kilns may be divided into two general classes, viz., *intermittent kilns,* and *continuous kilns.* Intermittent kilns may be further sub-divided into *up-draught kilns* and *down-draught kilns.* Continuous kilns are seldom used in connection with hand molding or in small plants of any type.

Up-draught Kilns. The up-draught kiln was at one time almost exclusively used in this country and is still largely used in small yards where the hand process is used.

The old-fashioned up-draught kiln is nothing but the green bricks themselves built into a pile about 20 to 30 feet wide, 30 to 40 feet long and perhaps 12 to 15 feet high. The sides and ends are plastered with mud to keep in the heat, and the top is covered with earth and sometimes roughly roofed.

The bricks are piled in such a way as to form a series of arched openings extending entirely across the kiln, and in these arches the fires are built.

The brick nearest the fires are badly over-burned, sometimes to vitrification, and are called "arch brick." The brick at the top of the kiln are under-burned, and are called "salmon brick," and only the intermediate brick are first-class building brick.

The modern up-draught kiln has permanent sides made of 12 or 16-inch brick masonry walls, and the heat is generated in ovens outside. The flames and hot gases enter the kiln through fire passages in the walls and arches made through the brick within the walls. This type of kiln is more economical of fuel than is the early type, and yields a much larger percentage of first-class brick.

The burning of a kiln requires about a week, after which time the openings are tightly closed and the kiln allowed to cool very slowly.

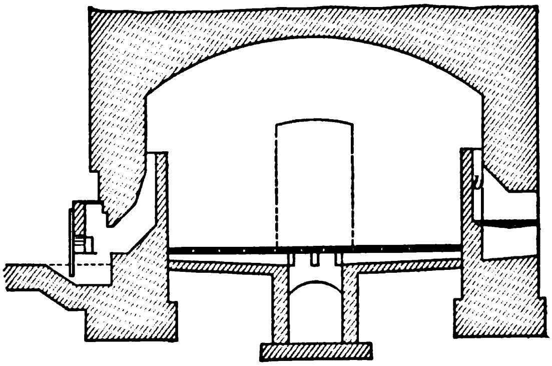

FIG. 131.—Down-draught Kiln. Vertical Section.

Down-draught kilns. Kilns of this type require permanent walls and a tight roof. The floor has openings connecting with flues leading to a stack. Down-draught kilns are usually built in a circular or bee-hive shape, but are sometimes rectangular. Fig. 131 shows a circular kiln in vertical section, and Fig. 132 shows the same kiln in horizontal section, the right half being a section above the floor, and the left half a section through the chimney flues below the floor. Heat is generated in outside ovens and the flames and gases enter the kiln through vertical flues (*b*, Fig. 131), carried to about half the height of the kiln. The heat therefore enters the brickwork at the top and is drawn downward by the chimney draught to the flues below the floor, and thence to the chimney or stack. The efficiency of the down-draught kiln is much higher than that of the up-draught kiln, and terra cotta and pottery, as well as brick, are burned very evenly in this type of kiln.

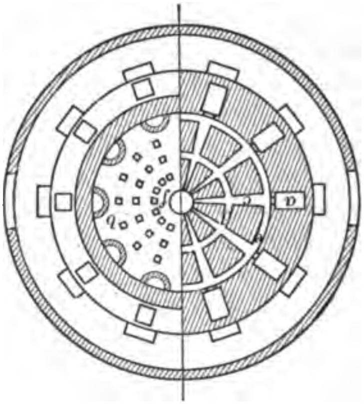

Fig. 132.—Down-draught Kiln. Horizontal Sections.

Continuous Kilns. Many patented types of continuous kilns are on the market, but all depend on practically the same principle. A number of chambers are connected in series, and also individually connected with a stack. The stack flues and the flues between chambers are provided with dampers. While one chamber is burning, the waste products of combustion are forced to traverse the whole series of charged chambers before reaching one which is open to the stack. The material is thus preheated before being fired, and a considerable heat economy effected. The Hoffmann ring kiln (Fig. 13) is typical of this class of kiln. Fuel is supplied to the chambers through holes in the roof of each chamber, and in the more modern types is burned on grates or in troughs placed in the upper part of each chamber. The flue openings are in the floor so that the down-draught principle is utilized. This type of kiln is expensive to install, but is more economical of fuel than any other kiln. The percentage of first-class brick is also high, provided that the fuel is burned on grates or in troughs, instead of in contact with the brick, as was the practice with the original Hoffmann kiln.

243. Sorting and Classification. Uses of Various Grades. In emptying the kiln, the bricks are commonly separated into various grades or qualities according to the degree of burning and freedom from imperfections. All bricks which show cracks or excessive kiln-marking as well as those which are badly warped must be put into an inferior class.

Classification and Uses of Building Brick. All of the classes of brick whose manufacture is discussed above are classed under the head of *common brick* or *pressed brick*. The three grades of common brick have been mentioned, viz.:

Arch or hard brick, those which, owing to their position in the kiln have been over-burnt, are apt to be misshapen, and are used only in footings and for the " filling " of brick masonry.

Red or well-burned brick, which amount to about half the output of the up-draught kiln and constitute the best grade of brick for all general construction purposes, and

Salmon or soft brick, those which have not been sufficiently burned, are too weak for use as a first-class construction material, but are used for masonry filling and unimportant work not calling for high strength or great durability.

Pressed brick or face brick are made by the dry-clay process as above noted or, using the commonly accepted meaning of the term, by repressing soft or stiff-mud process bricks. They are smooth and hard, have true surfaces and sharp angles, and can therefore be laid with a minimum thickness of mortar joint. The advantages they possess in appearance favor their use in the facing of masonry, and the fact that they are much more expensive than common brick practically limits their use to that purpose.

Glazed and enameled brick. Glazed brick are those made by coating one side of unburned common brick with a thin layer of what is called " slip," a composition of ball clay, kaolin, flint, and feldspar, and then applying a second coat of transparent glaze resembling glass. The slip gives the color to the brick, and the glaze melts upon firing the brick, and forms a smooth transparent coating over the white slip.

Enameled brick are made from a clay of peculiar character, generally containing fire-clay, and the enamel is applied either to the unburnt brick or to the finished brick. In burning, the enamel fuses and unites with the body of the brick. It does not become transparent, but gives its own color to the brick.

Enameled brick are expensive and more difficult to make than glazed brick, but the former are generally considered the more durable.

Both glazed and enameled brick are usually made pure white in color, they do not acquire odor, and are impervious to moisture. They are, therefore, particularly adapted for use in interior finishing, lavatories, hospitals, etc.

Ornamental brick are simply common brick which have been formed in a special mold which imparts some relief design to the face. Specially selected clays may be used to impart some desired uniform color. They are made in various sizes and shapes.

Tapestry brick are made by the stiff-mud process, and subsequently have their surfaces roughened by cutting off a slice by a wire. Tapestry brick are much used as a face brick.

Roman tile are pressed or repressed brick of unusual form, their face dimensions being 12 by 1½ inches, and the depth 4 inches.

Hollow brick are common brick made by the stiff-mud process, a special die which forms hollow spaces through the length of the brick being used. This produces a light brick which is much used for interior wall facing and for partitions. When their surface is grooved to afford a hold for plaster, hollow brick are called *furring brick.*

Sand-lime brick are not made from clays, but since their uses are identical with those of ordinary building brick, their manufacture will be separately discussed at this point.

MANUFACTURE OF SAND-LIME BRICK

244. General. There are several classes of brick which are manufactured by combining sand and lime together in proper proportions. Only one of these is important as a commercial article, however, and entitled to the name " sand-lime brick."

Sand brick, or the " kalksandstein " of the Germans, are made up of a mass of sand bound together by calcium carbonate (calcium silicate also, according to the claims of their advocates), hardened by exposure in the air, or in air particularly charged with carbon dioxide, such as the gases from a lime kiln.

Mortar brick which have simply calcium carbonate as the binding material, are really simply blocks of lime mortar hardened in air. They are structurally weak and unfit to be used as a building material.

Sand-lime brick are made from the same raw materials, but with much more care by a materially different process. The binding material is here not definitely established. The bricks are molded under pressure, and they are hardened in an atmosphere of steam while under pressure.

245. The Sand. Almost any sand may be used if the process used be properly varied to suit the properties of the sand. A comparatively pure and clean sand is, however, essential to cheap manufacture. One well-graded in size and not too coarse is preferable.

Fineness and Granulometric Composition of Sand. Experiments made by Professor M. Gasenapp in the laboratory of the Polytechnic Institute at Riga * show clearly that the binding action of lime and sand proceeds much more rapidly when the sand is very fine. From the standpoint of denseness and strength, however, a sand of such composition

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* Thonindustrie Zeitung, Oct., 1900.

as to secure a minimum of voids is preferable. A composition of at least four parts of sand which is between the 20-mesh and the 100-mesh screen size to one part of sand finer than the 150-mesh has been found to give a brick of maximum compressive strength.

From the standpoint of weathering qualities it is apparent that a well-graded mixture will make a brick of lowest absorption and hence least apt to disintegrate due to weathering.

Impurities in Sand. The principal impurities in sand are clay, iron oxide, mica, and feldspar. Clay was found by Mr. Peppel * to have a marked influence in decreasing both the compressive and tensile strength of sand-lime bricks. The addition of 20 per cent clay decreased the strength one-third. Iron oxide is probably inert and the same is true of mica. More than very small percentages of mica are injurious, however, in a purely mechanical way, just as they are in cement mortars. Feldspar was found by Mr. Peppel to be detrimental to crushing strength, but beneficial to tensile strength when 10 per cent was present.

246. The Lime. Quality and Quantity Required. Either high-calcium lime or dolomitic lime may be used, but the former, whenever obtainable, is preferable. Mr. Peppel found the high-calcium lime gave a materially stronger brick both in compression and in tension.

The amount of lime used in practice varies from about 5 to 10 per cent. Mr. Peppel found that while there is an increase in strength with increase in lime, the increase is less marked as the lime percentage is increased, and he concluded that the strength gained by addition of lime beyond 10 per cent would not justify the additional cost.

All of the earlier writings on the subject of sand-lime brick assert that the hardening process employing steam under heavy pressure results in the formation of calcium hydrosilicate by combination of the lime with the silica of the sand.

It has never been proven that any chemical combination does take place between lime and silica at such low temperatures as are encountered in the hardening of sand-lime bricks, and all investigations of the formation of calcium silicates tend to prove that such compounds certainly cannot be formed at temperatures below 900° C. The calcium hydrosilicate theory has therefore been generally abandoned, though a more reasonable hypothesis has not been advanced to account for the observed fact that the steam pressure treatment does produce a material whose hardness and mechanical strength cannot be accounted for if the binding agent is ordinary calcium carbonate alone.

247. Preparation of the Sand. The preliminary treatment of the sand is dependent first upon the source of the sand, and second, upon the

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* Geol. Sur. of Ohio, 1906.

subsequent details of manufacture. If a soft sand-stone rock is used it must first be crushed and then screened to separate out the larger particles. If the sand be obtained by dredging it must be dried, the amount of drying being dependent upon the subsequent manner of operation. If an excess of clay is present, or if it be a seashore sand contaminated with the salts of sea-water, washing and subsequent drying are required. If the sand does not contain a sufficient proportion of very fine quartz sand it is necessary to pulverize a portion of it in a tube mill or other type of fine-grinding machine and add the pulverized sand to the natural sand. In some foreign works it is considered advantageous to roast the sand before mixing, the idea being that chemical action is rendered more active and complete thereby. The efficacy of this latter expedient is open to some doubt.

248. Preparation of the Lime. The preparation of the lime is simply a matter of hydrating or slaking it either before or after the addition of the sand. In the majority of cases the lime is slaked before mixing with the sand, the one exception being the use of a very wet sand. In this event the unslaked lime may be mixed with a portion of the wet sand and thus slaked, and the balance of the sand after being dried is added to the mix. With a moist sand the lime may be slaked to a putty before being mixed with the sand. The best method, however, consists in the use of dry sand and dry hydrated lime, the latter prepared by one of the methods described under the head of hydrated lime.

249. Mixing. The thoroughness of the mixing process is the most essential detail of the entire process. Probably the best method of thoroughly incorporating the 5 to 10 per cent of lime used with the sand and water consists in mixing the lime and sand in a tube mill and then adding water to the mix in a pug-mill. The latter delivers the mix to a bin where it is allowed to stand for some hours before being delivered to the press.

250. Pressing the Brick. Owing to the gritty character of the mix it is not possible to make wire-cut sand-lime brick. They are therefore made in a mold under pressure in exactly the same manner that dry-clay brick are made. Experiments made by Mr. Peppel indicate that brick of maximum strength are obtained when the pressure to which the brick are subjected in the mold is about 15,000 pounds per square inch.

251. Hardening. The brick are not allowed to harden in air, but are hardened in closed chambers subjected to steam under a pressure of from 100 to 150 pounds per square inch. The hardening kettle used, Fig. 133, is a horizontal cylinder of steel, provided with a removable steam-tight cylinder head and tracks upon which cars carrying the brick are run into the cylinder. Experiments made by Mr. Peppel led to the conclusion that first quality sand-lime brick may be hardened in four hours if 150 pounds steam pressure is used, in six to eight hours at 120 pounds and in eight to twelve hours at 100 pounds. The usual practice is to employ steam under about 120 pounds pressure, maintained for from eight to ten hours.

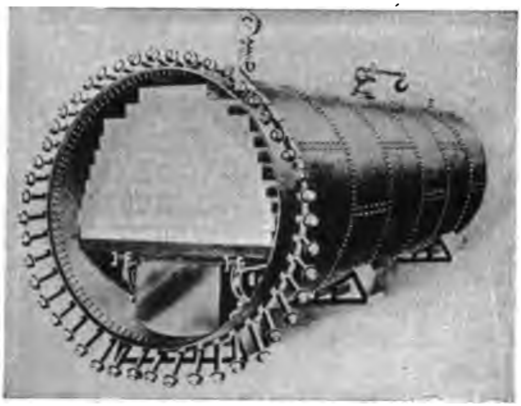

Fig. 133.—Hardening Cylinder for Sand-lime Brick.

252. Uses of Sand-lime Brick. Sand-lime brick, when properly made, have been found an eminently suitable material for general construction purposes in any situation where pressed brick may be used. Their use has as yet been confined largely to the vicinities of the plants where they are made, but the industry shows a healthy growth with an accompanying increase in structural use. In 1913 there were 68 plants making sand-lime brick in the United States, having a total yearly output of about 190,000 M, valued at about $1,238,000.

MANUFACTURE OF PAVING BRICK

253. General. The requisites for a good paving brick are that it shall be hard enough to resist the abrasive action caused by street traffic; tough, so that it will not be broken by the impact of wheels, horses' hoofs, etc.; and non-absorptive, so that it will resist weathering well. Its manufacture differs from that of common brick, first, in that the selection of a suitable clay is more limited, and second, in that it must be burned at a much higher temperature, vitrification or at least incipient vitrification being required.

254. The Clay. Three classes of clays have been used in the manufacture of paving brick, viz., surface clays, impure fire clays, and rock clays or shales.

Surface clays are generally unfit for use as paving-brick clays because, on account of their highly silicious character, the range of temperatures between incipient and viscous vitrification is so short that only a small proportion of the kiln charge is properly burned.

Impure fire clays are used to a slight extent, but are usually very hard to burn properly. A pure fire clay cannot be vitrified; it is necessary, therefore, that there be present at least from 5 to 7 per cent of fluxing impurities (iron, lime, magnesia and alkalies), and the higher this percentage is the more cheaply it can be burned. These clays possess one advantage in that it is usually impossible to over-burn them, and the burning need not be watched so carefully, as in the case of the surface clays and the shales.

Shales or rock clays are used for practically all paving brick made at the present time. They occur in larger bodies than either of the other classes of clays and, although the expense of crushing is increased owing to their rock nature, they are so impure that the range of vitrification is often as much as 400°, making them an especially valuable material for paving-brick manufacture.

Preparation of the Clay. The shale banks are usually worked by steam shovel with or without blasting of the rock. Fireclays are mined in underground chambers like coal, and surface clays are usually handled by hand tools, scrapers, carts, etc.

Upon delivery at the plant, shales are crushed either in dry pans (edge runners), rolls, or centrifugal disintegrators. Fireclays and surface clays are handled in the same types of disintegrators but with less expense. The crushed clay is screened to remove all particles not passed by about a 20-mesh sieve, and delivered to the pug-mill where just sufficient water is added to make a stiff mud.

255. Molding and Drying. Practically all paving brick are now made by the stiff-mud process above described, the machine being usually of the auger type. The size of the die is larger than in the case of building brick, since the usual size of paving brick is about 3½ inches wide by 8½ inches long and 4 inches deep. Both side-cut and end-cut brick are made, the choice depending largely upon local conditions at each plant.

Many paving bricks are repressed immediately after molding, the repressing being useful in making the brick more uniform in size and shape. The repressing dies are so formed that the edges of the brick are rounded off, lugs are made on the sides to separate the brick slightly when laid in the street, and the imprint of the manufacturer is placed on the brick.

Paving bricks which are simply wire cut without being repressed are usually what are called "wire-cut lug brick." They differ from ordinary wire-cut brick only in that the wire-cutting mechanism is so contrived that instead of the wires cutting plane surfaces, they cut planes which are interrupted by two high points which serve as lugs. Such bricks must be side cut, not end cut.

"Hillside" brick are ones which have one of the upper edges beveled off to make a pavement less smooth.

Drying of paving brick is accomplished by exactly the same methods as those used for ordinary stiff-mud brick. The use of a drying tunnel is most commonly resorted to.

256. Burning, Annealing and Sorting. The burning of the brick is accomplished either in the down-draught kiln or the continuous kiln above described. The burning requires from seven to ten days as a rule, and the temperature is a bright cherry heat (1500 to 2000° F. for shales, and 2000 to 2800° F. for fireclays), whereas only a red heat is attained in burning hard building brick. The temperature required varies according to the clay used, and the proper temperature of vitrification for a given clay must not be exceeded, since it results in the brick becoming softened. At the best the brick in the lower portion of the kiln are usually kiln-marked owing to the weight of the charge above. When the brick are thoroughly burned the kiln must be tightly closed and allowed to cool down slowly for several days. Thus the brick are annealed and acquire a great deal more toughness than when quickly cooled.

The brick must be sorted in emptying the kiln. The upper courses will be very hard burned but possibly air-checked. They are excellent brick for foundations or sewers and are sometimes called sewer brick. From the zone of checked brick to within a few courses of the bottom, the brick should be No. 1 pavers; the lower courses have not been sufficiently heated to be vitrified and are classed as No. 2 pavers. These latter brick are much used as building brick, for which purpose they form a most excellent material.

With fireclay as high as 80 to 90 per cent of the kiln charge are No. 1 pavers, and with shale about 60 to 80 per cent of No. 1 pavers are obtained.

MANUFACTURE OF FIRE BRICKS

257. General. The manufacture of firebrick which are able to withstand the moderate heat encountered in ordinary situations such as chimneys, flues, etc., has been carried on for a great many years. It is only comparatively recently, however, that a demand has arisen for firebrick and fire blocks to be used (especially in the metallurgical industries) where they must not only withstand extremely high temperatures, but must also have certain chemical proclivities which make them withstand an oxidizing or a reducing action, either of which may be encountered in one type or another of metallurgical furnace.

The principal materials from which firebrick are made are fireclay, silica rock, ganister rock (natural or artificial), magnesia, bauxite, and chromite. The process of manufacture varies according to the class of brick and the nature of the raw materials used; the various processes will therefore be separately considered.

258. Acid Bricks. *Fireclay Brick.* One of the most refractory materials for use in the manufacture of firebrick is ordinary fireclay, to which flint clay, burnt fireclay, sand, or other refractory material has been added to prevent undue shrinkage in drying and burning. Fireclays owe their superiority over brick clays as a refractory material to their greater purity, i.e., the absence of the fluxing impurities iron, lime, magnesia, and the alkalies. In order to afford a contrast between the composition of fireclays and typical brick clays the following table has been selected from Ries' " Economic Geology."

COMPOSITION OF FIRECLAYS AND BRICK CLAYS

	SiO_2.	Al_2O_3.	Fe_2O_3	FeO.	CaO.	MgO	Alk.	H_2O.	CO_2.	SO_3.
Plastic fireclay.............	57.62	24.00	1.90	1.20	0.70	0.30	0.70	13.20	...	0.35
Flint fireclay...............	59.92	27.56	1.03	..	Tr.	Tr.	0.64	10.82		
Brick shale................	54.64	14.62	5.69	..	5.16	2.90	5.89	4.59	4.80	
Calcar. brick clay..........	38.07	9.46	2.70	..	15.84	8.50	2.76	2.49	20.46	
Blue shale clay............	47.92	14.40	3.60	..	12.30	1.08	2.70	4.85	9.50	1.44

Manufacture. Fireclays are mined in underground workings, and the plastic clay which is mixed with the fireclay is handled in the manner described for common brick clays. Each material is separately ground, usually in a dry pan, after which they are screened and mixed in the required proportions. The relative amounts of the two ingredients vary greatly according to the clays used, but usually approximate about equal proportions. The use of burnt fireclay or sand is more common in England and Germany than in this country.

The mixing of the materials is accomplished either in an open mixer, or in the pug-mill, where the required amount of water is added. The plastic mass delivered from the pug-mill is usually allowed to stand for some time in order to allow the moisture to become more perfectly distributed before being sent to the molder or brick machine. A large proportion of the brick are molded by hand by a process that is practically that of slop molding above described. Either the stiff-mud process or the dry-clay process may be used, however. The drying of the brick is effected in the manner that would be used for ordinary clay brick made by a similar process, and the firing is done in down-draught or continuous kilns. The temperature of burning must be higher than is used with ordinary clay brick in order that there may be no further shrinkage of the brick when subjected to high temperatures in use as a furnace lining, or in any similar situation. A temperature of from 2500 to 3500° F. is required for proper burning, the lower figure applying to the lower grade of ordinary firebrick and the upper figure for the highest grade. The cooling should be rapid till the temperature is below 2500° F., after which point slow cooling is required.

Silica Brick. Silica brick are made of silica sand or silica sandstone rock, mixed with a very small percentage of lime, which acts as a binding material. Silica brick made of the purest grade of materials will withstand a temperature of about 3900° F., while the usual commercial article will fail at temperatures above about 3700° F. They are therefore slightly less refractory than the highest grade fireclay bricks, but are superior to the ordinary run of fireclay bricks. Silica bricks can be made only of very pure materials (98 per cent or more silica), since small percentages of the fluxing impurities materially increase fusibility. The brick are extremely hard and brittle and upon being heated expand, instead of shrinking, as clay brick do. This expansion, amounting to about 10 per cent, must be allowed for in laying the brick.

Manufacture. The silica rock is crushed between rolls or in a gyratory crusher and then pulverized in an edge-runner mill. In this latter mill lime is added, 1½ to 2 per cent being used, and water is mixed with the mass. Usually the lime and water are added together in the form of lime-milk. The final composition of the brick will be 96 to 97 per cent silica, 1½ to 2 per cent lime, and 1½ to 2 per cent impurities.

Usually silica brick are molded by hand, dried in dry-rooms or drying tunnels, and fired in down-draught kilns. No particular precautions are necessary in firing, the temperature required being from 2600 to 3200° F. The cooling down of the brick must be accomplished with the greatest care, however, since silica bricks are very sensitive to sudden changes in temperature.

A very high-grade silica brick is now produced by the process used in the manufacture of sand-lime brick. The materials are mixed as a stiff mud, molded in a press, and hardened under steam pressure for about eight or ten hours.

Ganister Brick. Ganister brick are intermediate in grade between fireclay brick and silica brick. They are made from ganister rock, which is a dense silicious sandstone containing about 10 per cent clay.

Ganister brick are made in a manner similar to silica brick except that lime is seldom added, since the clay forms a sufficient binder. Firing is done at about the same temperature as that required for silica brick and the cooling must be slowly and carefully accomplished.

259. Basic Bricks. *Magnesia Brick, Bauxite Brick.* All of the firebricks above described are of an "acid" character, that is, being composed largely of free silica, they are capable of acting as an acid material at high temperatures, and of fluxing in contact with a basic material such as lime. By decreasing the silica content and increasing the alumina content the material may be rendered "basic" in character.

Materials which are used for making basic bricks are principally "bauxite" and "magnesia." Bauxite brick are made by grinding bauxite (85 per cent or more Al_2O_3) in an edge-runner, mixing with about 25 per cent clay in a pug-mill where water is added, and molding by hand or by the stiff-mud machine. Burning is done at a temperature of about 2800° F. The composition of bauxite brick is about 70 per cent alumina, 16 to 18 per cent silica, and 12 to 14 per cent ferric oxide. Shrinkage upon heating is excessive, and the bricks are structurally very weak.

Magnesia brick are made from a mixture of caustic magnesia (obtained by burning magnesite in a lime kiln) and sintered magnesia which contains a small percentage of ferric oxide to act as a flux. Dolomite (double carbonate of lime and magnesia) is sometimes used to make magnesia brick, but is inferior to a mixture of sintered and lightly burnt magnesia.

The materials are ground in an edge-runner mill, water is added in a mixer or pug-mill, and the bricks are molded under a heavy press. Drying must be carefully carried out in drying houses or drying tunnels and firing is accomplished in down-draught kilns or in gas-fired kilns at a temperature of from 3300 to 3450° F. The shrinkage of magnesia brick is irregular and excessive.

Magnesia and bauxite bricks have a remarkable power of resisting the corrosive action of slag and limestone at high temperatures, but are extremely sensitive to the action of silica and acids generally, and both are very weak structurally. They are used in the lining of basic steel furnaces, in lead smelters, in cement kilns, etc.

260. Neutral Firebricks. Chromite (chrome iron ore) is principally used for the manufacture of a refractory brick, which is practically "neutral." Chrome brick are used in metallurgical furnaces to separate basic and acid brick linings, when the former is used for the lining of the melting chamber in contact with a basic charge and the latter used for the top arches, where greater mechanical strength is needed. Chromite used alone is almost without binding power, and is therefore usually mixed with fireclay or bauxite in such a proportion that the bricks contain about 50 per cent chromium oxide, 30 per cent ferrous oxide, and 20 per cent alumina and silica.

Chrome brick are made by crushing the materials in edge-runner mills and molding under heavy pressure, as in the case of silica bricks. The firing temperature is about 3000° F.

TERRA COTTA

261. General. Terra cotta is composed of practically the same material as bricks, but requires a carefully selected, finely divided homogeneous clay which burns to a desirable color with a slight natural glaze.

262. Decorative Terra Cotta. Terra Cotta Lumber, Building Blocks and Fireproofing. Usually no single clay is used in the production of terra cotta, but each shade and tint requires the mingling of different clays.

The clays after delivery at the factory are separately ground in wash-mills or edge-runner mills, mixed with grit and water in pug-mills and separately deposited in layers or strata. As many as ten or twelve strata are thus piled up, and from this mass perpendicular cuts are taken and the whole mixed together in a pug-mill into a plastic mass.

The subsequent manner of molding depends largely upon the character of the ware being made. *Decorative terra cotta*, used for architectural purposes, is usually made by hand molding in plaster casts which have been made by skilled hand work. Intricate designs are modeled without a mold and green casts are often further carved by hand before being dried and burnt. After drying and before burning a coating of "slip" is applied to the ware. This slip is made up of clay, feldspar, flint, etc., is opaque, and imparts the color desired for the finished product. Either a dull or a bright glazed finish may be procured.

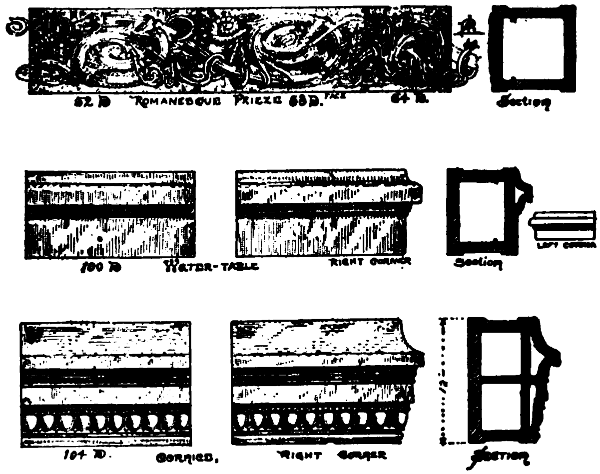

FIG. 134.—Decorative Terra Cotta.

Burning is done with extreme care to prevent either distortion or discoloration by flames or gases. Special kilns in which the ware does not come in contact with the gases are commonly used. Fig. 134 shows a number of typical designs in decorative terra cotta. Very elaborate designs of high artistic merit are sometimes executed. It is not practicable to burn terra cotta in very large units, so it is often necessary to make a complete design of many comparatively small sections.

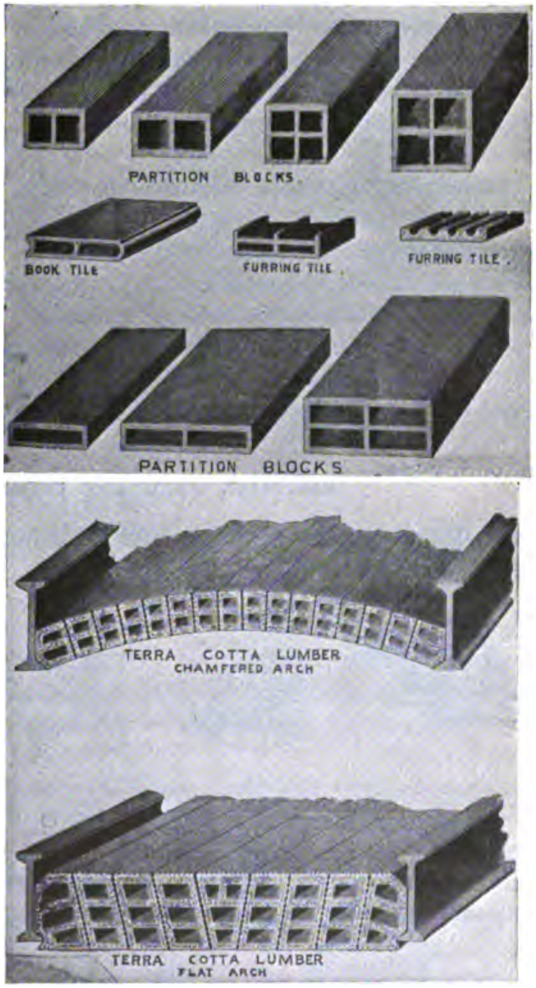

Fig. 135.—Terra Cotta Lumber.

Terra cotta blocks or terra cotta lumber is an entirely different material, made for strictly structural purposes and not at all for decorative effect, being always covered by plaster or mortar.

The raw materials used for terra cotta lumber are terra cotta clays and finely cut straw or sawdust. The materials are thoroughly mixed (after grinding) in a mixer or pugmill to form a stiff mud, which is thereupon forced through a die by a plunger-type machine. Practically all terra cotta lumber is made of hollow construction, with walls about 1 inch thick, and with partition walls about $\frac{3}{4}$ inch thick.

The blocks are wire cut, as in the case of ordinary stiff-mud bricks, and are carefully dried before firing. Firing is usually done in a down-draught kiln and especial care is required in stacking up the ware in such a manner as to prevent distortion and unequal heating. The temperature of burning is sufficient to burn out all the straw or sawdust incorporated in the mix, and leaves a very light and porous material which is soft enough to be cut with a saw and into which nails or screws may be driven with ease. Fig. 135 illustrates various common forms of terra cotta lumber.

Hollow building blocks and fireproofing are absolutely the same thing as terra cotta lumber except that no straw or sawdust has been incorporated with the clay and the burning is carried to a higher temperature, almost to vitrification in fact. They are therefore much harder than terra cotta lumber and are not porous, but resemble ordinary hard-burned brick.

Hollow building blocks are made in exactly the same shapes as terra cotta lumber and have the same uses. Both are used extensively as a fireproof material for constructing exterior and partition walls, ceilings, floor arches, furring for outside walls, roof sheathings, and jackets around beams and columns of steel-framed buildings.

Porous terra cotta is more conveniently handled, due to its softness and easy-cutting qualities. It is also claimed to be tougher than hard-burned blocks. The latter are stronger, however, under static load.

ROOFING, WALL, AND FLOOR TILES

263. Roofing Tiles. Roofing tile must be hard, strong, and non-absorptive. They are made by a process similar to that employed for pressed brick except in the case of the flat forms, which may be made by the stiff-mud process. The principal forms of roofing tile are shown by Fig. 136. Shingle tile are laid like slate, being perfectly flat; mission style tiles are in a measure interlocking, being segments of hollow cones;

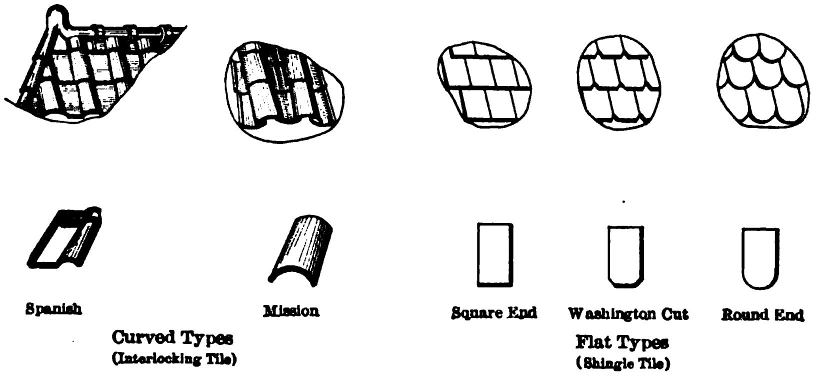

Fig. 136.—Roofing Tile.

and Spanish tile are distinctly interlocking. The two latter forms are made by repressing slabs of green clay. The clay is selected with greater care than in the case of ordinary brick, and burning is done at a sufficiently high temperature to insure hardness, strength and non-absorptiveness.

264. Wall Tile. Wall tile are of two general types according to the process employed in making them—" dust-pressed " tile and " plastic " tile. The clay used in making dust-pressed tile may be a fireclay, or even a red-burning shale clay, if artificial coloring is to be used, but if a white body is required a mixture of clays, feldspar, flint, etc., is employed. These materials after grinding and mixing are made up into a thin cream which is strained through a silk screen. The water is now drained or squeezed out and the material is ready to be molded if the plastic process be used. For dust-pressed tile this material is dried, crushed to powder, moistened slightly by steam, and stored until used.

Molding is done in a dry press and any desired relief pattern is imprinted by the moving plunger of the press. The ware is now placed in fireclay boxes in which it is burned out of contact with the flames. After burning, a transparent or opaque glaze is applied, coloring matter being introduced if desired. A second firing is now required to fuse the glaze. Either a bright or a dull glaze is obtained by proper selection and application of the glaze materials.

Plastic tile are made in practically the same manner as " dust-pressed " tile, except that a mixture of soft clay and powdered burnt clay is used, and the molding is done immediately after mixing and tempering. Molding is done by hand in plaster molds which may or may not impart a design to the face. In the latter case the tile may be removed from the mold when partly dry and a design modeled by hand. Sometimes plastic tile are not glazed, and in that event no second firing is required. Most wall tile are dust-pressed tile.

265. Floor Tile. Floor tile are made from the same materials as dust-pressed wall tile and the process employed is practically the same. Fireclays and red-burning clays are most commonly used, however, and if white-burning materials are used coloring matter (metallic oxides) is usually introduced. No glaze is used and only one firing is necessary.

DRAIN TILE AND SEWER PIPE

266. Drain Tile. Drain tile are made from a red-burning clay or mixture of clays of the character of those used in making terra cotta lumber. The clay is handled by the stiff-mud process, issuing from a special die as a hollow cylinder, which is cut to convenient lengths by wires.

Burning is conducted at temperatures compatible with the production of a very porous product, which possesses a considerable degree of mechanical strength, but is not vitrified or glazed.

267. Sewer Pipe. Sewer pipe is not intended to be porous or absorptive like drain tile, but on the contrary is made from clays which will form a very non-porous product of low absorption. The stiff-mud process of mixing and molding may be used if the pipes are not fitted with socket ends. For socket pipes the dry-press must be used, the form being imparted by a mold. Special shapes, such as elbows, Ys, and Ts, are similarly molded.

After drying in steam chambers the ware is burned in down-draught kilns. A special glaze called " salt glaze " is imparted to all surfaces of the pipe by throwing common salt into the kiln fires after a temperature of about 1150° C. has been attained. The sodium vapors freed by heat pass through the kiln, and by combination with the clay form a dense hard glaze, which renders the pipe practically non-absorptive.

Sewer pipe are intended exclusively for use as conductors of water, sewage, etc., and are laid with tight cement joints. They therefore do not take up and carry off the water in wet soil as drain tiles do.

PROPERTIES OF BRICKS OF ALL CLASSES

268. Crushing Strength. Since, as will be later shown, the strength of brick masonry is only a fraction of the strength of the brick, the compressive strength of individual bricks is of only relative value in that it affords a basis of comparison between different kinds of brick.

The following table is inserted to show the approximate strength of the several grades of brick. The table has been selected partly from the Watertown Arsenal tests of 1895, 1897, and 1906 and partly from tests made by the author. The color is noted in each case simply by way of general description. It is not an indication of the degree of burning except when brick from one class of materials only is being considered. From inspection of the table we may conclude by way of a summary that the compressive strength of average good building brick is about 4000 pounds per square inch; pressed brick about 8000 pounds per square inch; sand-lime brick 3000 to 4000 pounds per square inch; paving brick 10,000 pounds per square inch; fireclay brick 3000 to 6000 pounds per square inch; terra cotta blocks, 4000 pounds per square inch; and architectural terra cotta 3000 pounds per square inch;

COMPRESSIVE STRENGTH OF BRICK

(POUNDS PER SQ. IN.)

COMMON BUILDING BRICK

Light-burned buff colored	2,987	1st brand
Hard-burned buff colored	3,570	1st brand
Hard-burned buff colored	4,561	2d brand
Well-burned cream colored	4,066	1st brand
Well-burned cream colored	4,845	2d brand
Well-burned cream colored	7,244	3d brand
Well-burned red colored	6,834	1st brand
Well-burned red colored	5,307	2d brand
Hard-burned red colored	9,520	1st brand

PRESSED OR FACE BRICK

Red face brick	12,898	1st brand
Red face brick	5,278	2d brand
Red face brick	8,327	3d brand
Red face brick	9,951	4th brand
Red face brick	7,067	5th brand
Buff-colored face brick	9,823	1st brand
Buff-colored face brick	9,264	2d brand
Buff-colored face brick	6,975	3d brand
Chocolate-colored face brick	6,582	1st brand

SAND-LIME BRICK

Red sand-lime brick	5,285	1st brand
Cream or brown sand-lime brick	3,517	1st brand
Light gray sand-lime brick	4,774	1st brand
Light gray sand-lime brick	5,098	2d brand
Light gray sand-lime brick	4,010	3d brand
Light gray sand-lime brick	2,535	4th brand
Light gray sand-lime brick	6,810	5th brand

PAVING BRICK

Red vitrified paving block	11,340	1st brand
Red vitrified paving block	13,316	2d brand
Red vitrified paving block	10,347	3d brand
Chocolate vitrified paving block	10,871	1st brand
Chocolate vitrified paving block	10,593	2d brand
Chocolate vitrified paving block	11,180	3d brand
Buff vitrified paving block	9,610	1st brand
Buff vitrified paving block	9,580	2d brand

FIRE BRICK

Buff fireclay brick	2,668	1st brand
Buff fireclay brick	6,299	2d brand
Buff fireclay brick	5,715	3d brand
Buff fireclay brick	4,525	4th brand
Buff fireclay brick	3,253	5th brand
Buff fireclay brick	6,278	6th brand
Buff fireclay brick	2,646	7th brand
Buff fireclay brick	8,589	8th brand

TERRA COTTA LUMBER

Partition tile 1 core (net section)	4,892	
Partition tile 2 cores (net section)	4,663	
Floor Arch Blocks 2 cores (net section)	3,591	
Floor Arch Blocks 4 cores (net section)	4,955	1st brand
Floor arch blocks 4 cores (net section)	3,730	2d brand

ARCHITECTURAL TERRA COTTA

White ornamental blocks	2,985
Buff ornamental blocks	3,520
Salmon ornamental blocks	2,975
Red ornamental blocks	2,830

269. Absorbing Power. The absorption of water by brick is often taken to be an important criterion of its probable durability. The freezing of water which fills the pores of brick will of course constitute a great disintegrating agency, but the importance of this factor is probably overestimated. In the first place, bricks which are structurally so weak that they are apt to suffer through frost action are not fit material for construction purposes, and in the second place, bricks, even though they are very porous, are seldom injured by frost for the reason that water does not fill the pores completely and hence is able to expand upon freezing without exerting a great disruptive force.

Tests of absorptive power of bricks are usually made to extend over so short a period that the results are apt to be misleading. The rate of absorption of bricks varies greatly, and therefore the usual forty-eight-hour test will sometimes show practically the ultimate absorptive power of a brick, while in other cases only a fraction of the ultimate absorption is shown.

In general the absorption shown by common building brick in a forty-eight-hour immersion test is from 12 to 18 per cent of the weight of the dry brick. For pressed or face brick the absorption is about 6 to 12 per cent; for sand-lime brick it is 12 to 15 per cent; for paving brick, 1 to 3 per cent; for fireclay brick, 8 to 12 per cent; and for unglazed building blocks of terra cotta, 10 to 15 per cent.

270. Transverse Strength. The transverse strength of bricks is one of the best indications of quality, not because bricks are often subjected to severe tests of their transverse strength in masonry, but because tests are easily made and an indication of their toughness is afforded. An indication of their approximate tensile strength is also obtained since the modulus of rupture bears a fairly close relationship to tensile strength. Experiments and experience show that the failure of brick masonry under compressive stress is really by failure and subsequent lateral flow of the mortar, thereby introducing tensile stresses in the bricks and causing cracks to open up in the masonry in the direction of the pressure. The fractured surface of a brick also affords a valuable indication of the care with which the materials have been ground and mixed, and the degree of burning is made evident to an experienced observer who is familiar with the normal appearance of the bricks under examination.

The modulus of rupture of common building bricks varies from about 500 pounds per square inch to about 1000 pounds per square inch; pressed bricks, 600 to 1200 pounds per square inch; sand-lime bricks, 300 to 600 pounds per square inch; paving bricks, 1500 to 2500 pounds per square inch; fireclay bricks, 300 to 600 pounds per square inch; and unglazed terra cotta building blocks, 500 to 1000 pounds per square inch.

271. Shearing Strength. The shearing strength of bricks as shown by tests is a property of little practical importance, chiefly because it is almost impossible to make the best results really show actual shearing strength. All methods of testing which have been devised are more or less subject to the same objection, i.e., the shearing stress is not acting alone, but bending is introduced, thus bringing tension and compression into play as well as shear.

Tests made at the Watertown Arsenal indicate that the shearing strength of common bricks is about 1000 to 1500 pounds per square inch; pressed bricks, 800 to 1200 pounds per square inch; sand-lime bricks, 500 to 1000 pounds per square inch; paving bricks, 1200 to 1800 pounds per square inch; and fireclay bricks, 500 to 1000 pounds per square inch.

272. Modulus of Elasticity. The modulus of elasticity of bricks is not a constant for any considerable range of loading. The elastic properties as shown by the stress-strain curve for a compressive test are quite similar to those of concrete and mortars. For ranges of loading not exceeding one-fourth of the compressive strength the modulus of elasticity of common bricks is about 1,500,000 to 2,500,000 pounds per square inch; pressed brick, 2,000,000 to 3,000,000 pounds per square inch; sand-lime bricks, 800,000 to 1,200,000 pounds per square inch; and paving bricks, 4,000,000 to 8,000,000 pounds per square inch.

BRICK MASONRY

273. General. Brick masonry was at one time considered as simply an inferior substitute for stone masonry, an estimation which may have been justified by facts at the time when almost all bricks were hand made from materials indifferently selected. At the present time, however, brick masonry built with bricks made by modern processes from carefully chosen raw materials, and with the aid of elaborate plant equipment, will for many purposes and situations equal or excel most stone masonry.

Brick masonry is usually cheaper than stone, it is more easily built with less skilled labor, it is a better fire resistant, and it compares well as regards durability with the best stone masonry. Only one class of stone masonry is stronger than the best brick masonry—cut stone masonry—and this is so much more expensive than brick that its use is largely barred except where great strength is the first requisite.

274. The Mortar and the Joints. Reference should here be made to the discussion of lime and lime mortar in Arts. 59 to 64. Lime mortar is used in building a great proportion of the brick masonry constructed in this country. As stated above the slower setting magnesian or dolomitic limes are generally preferred for bricklaying on account of the fact that the rapidity of laying is increased by their choice in preference to high-calcium limes. Hydrated lime is now coming into quite general use in preference to lump quicklime. Natural cement and Portland cement are often added to lime mortar to secure greater strength. The former is generally believed to confer greater plasticity and better working qualities than the latter.

The proportions commonly used in lime mortars are either one part lime to two parts sand, or, more commonly, one part lime to three parts sand.

Ordinary lime mortar hardens very slowly and the gain in strength is too slow when high walls are built rapidly. For such construction natural cement or Portland cement should constitute a portion of the mortar or better still, a Portland cement mortar may be used altogether.

For all construction below grade, or in any situation where moisture is often encountered, also in heavily stressed brick masonry in piers, arches, etc., cement mortar should always be used instead of lime mortar.

All brick should be laid with the minimum thickness of joints consistent with proper bedding. Common bricks are usually somewhat rough and uneven, but may be and should be laid with joints from $\frac{3}{16}$ to $\frac{3}{8}$ inch in thickness. It is commonly specified that the height of eight courses of brick masonry shall not exceed the height of eight bricks laid dry by more than 2 inches.

Pressed brick, being usually smooth and true, are laid with joints not exceeding $\frac{1}{8}$ or $\frac{3}{16}$ inch in thickness.

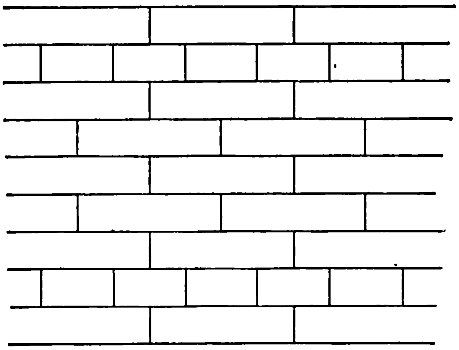

FIG. 137.—Common Bond of Brickwork.

275. Bond. Bond in brickwork is the arrangement of the bricks in courses resorted to for the purpose of tying together all parts of walls more than one brick in thickness by the action of the weight of the overlying masonry. The commonly adopted bonds for laying brick masonry are common bond, English bond, and Flemish bond.

In common bond, Fig. 137, all of the outside brick are laid as stretchers for from four to six courses, and then a course of headers is placed. This type of bond is more generally used than any other in this country.

In English bond, Fig. 138, heading and stretching courses alternate. This is the strongest type of bond, but has not a pleasing appearance and is seldom used except in England.

In Flemish bond, Fig. 139, headers and stretchers alternate in each course, each header being centrally placed with respect to a stretcher in the course below. This is a strong bond, but requires cutting brick for each course at corners.

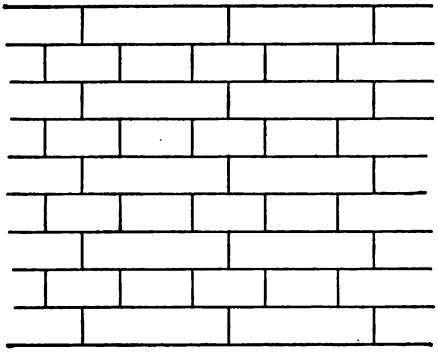

Fig. 138.—English Bond of Brickwork.

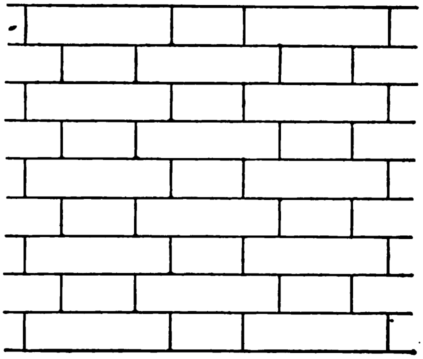

Fig. 139.—Flemish Bond of Brickwork.

None of the above types of bond is applicable in walls faced with face or pressed brick, the reason being that the face brick are smaller and laid with thinner joints than the common brick of the filling or backing, so that the level of the beds is not the same for the facing and the backing. It is also not usually considered desirable to destroy the symmetry of the face by introducing headers. It is therefore the practice to tie the facing of the backing by some sort of metal tie, one form of which is shown in Fig. 140.

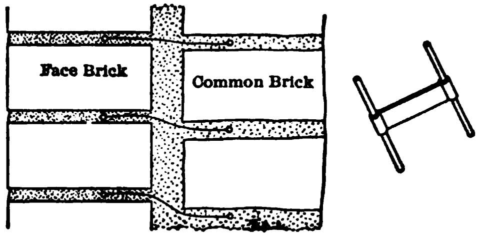

Fig. 140.—Metal Face Brick Ties.

276. Laying the Brick. Mortar, unless very wet, does not adhere to dry brick nor set properly, for the reason that the water in the mortar is absorbed by the bricks. All bricks should therefore be wet before being laid. This provision is one of great importance, but is a very difficult one to enforce since it makes a material difference in the amount of labor involved. It is difficult to lay pressed bricks dry, so there is not usually so much difficulty encountered on this score in the case of pressed brick as in the case of common brick.

The proper method of laying brickwork consists in spreading a layer of mortar along the outer edge of the last course of bricks with the trowel, pressing the brick into place with a sliding motion which forces the mortar to fill the joint, scraping off the excess mortar squeezed out on the face of the wall by the trowel, and applying this mortar to the outer vertical angle of the brick just laid to fill the next joint. After the two outside courses (face and back) have been laid in this manner the space between should be bedded with soft mortar and the filling brick placed with a similar sliding motion.

Fig. 141.
Pointing Brickwork.
(Incorrect.)

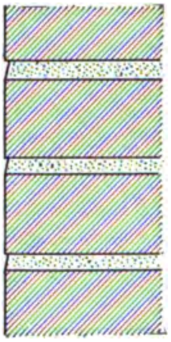

Fig. 142.
Pointing Brickwork.
(Correct.)

After several courses of brick have been placed the joints are "struck" on the face side of the wall by means of the point of the trowel held obliquely. Fig. 141 shows the easiest and cheapest way of striking the joints, but for the outside or weather face of walls the joints should be struck as shown in Fig. 142.

Strength of Brick Masonry

277. General. The appearance and durability of brick masonry is usually of greater importance than the actual crushing strength. In piers, however, and occasionally in arches and in the lower portion of the walls of high buildings built without a steel or concrete frame, the stresses encountered may be sufficiently high to make the crushing strength of the brick work an important consideration.

The strength of brick masonry is always much more a function of the mortar used, the bond, and the workmanship than a function of the strength of the individual bricks. Where high stresses are encountered cement mortar must invariably be used, and this is particularly true when a heavy load must be carried within a short time after the masonry is laid.

278. Strength of Brick Masonry Shown by Tests. The tests quoted below comprise a summary of tests of twenty-four brick piers about

12 inches square and 8 feet high made at the Watertown Arsenal.* The two varieties of pressed bricks tested gave lower column strength with all mortars than did the better class of bricks molded without pressure. This is probably accounted for by a lower bond or adhesion between the bricks and the mortar.

These tests clearly show the importance of using cement mortar in preference to lime mortar where strength is an important consideration. The strength of the 1 : 3 cement mortar masonry is approximately twice the strength of the lime mortar masonry, while there is little gained by the use of neat cement instead of 1 : 3 cement mortar except in the cases of the piers built with the highest quality bricks where the mortar of neat cement develops a greater proportion of the strength of the bricks.

CRUSHING STRENGTH OF BRICK PIERS

WATERTOWN ARSENAL TESTS, 1904

Age 6 months

Description of Brick.	Compress. Strength. Lbs. per Sq.in.			Per cent of the Ave. Crush. Strength of Brick.		
	Neat Port.	1 Port., 3 Sand.	1 Lime, 3 Sand.	Neat Port.	1 Port., 3 Sand.	1 Lime, 3 Sand.
FACE BRICK						
Dry pressed face brick.....	2880*	2400	1517	26	21	13
Re-pressed mud brick......	1925	1670	1260	28	25	19
COMMON BRICK						
Wire-cut stiff-mud brick ...	4021	2410*	1420	31	19	11
Hard sand-struck brick.....	4700*	1800*	994	42	16	9
Hard sand-struck brick.....	1969	1800	733	44	40	16
Hard sand-struck brick.....	1400	1411	718	24	24	12
Light-hard sand-struck brick	1510*	1519	732	23	23	11
Light-hard sand-struck brick	1061	1224	465*	20	23	9

* Tested at age of 1 month.

279. Pressures Allowed in Practice. The following table lists the safe working stresses for brick masonry recommended by a committee of Chicago engineers and architects, to be incorporated in the building laws of that city. The table represents very conservative practice:

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* Tests of Metals, 1904, pp. 419–449.

SAFE LOADS ON BRICK MASONRY

Description of Brick.	Kind of Mortar.	Safe Load, Lbs. per Sq.in.
Paving brick	1 : 3 Portland	350
Pressed and sewer brick (strength 5000 lbs.)	1 : 3 Portland	250
Select hard common brick (strength 2500 lbs.)	1 : 3 Portland	200
Select hard common brick (strength 2500 lbs.)	1 Portland, 1 lime, 3 sand	175
Common brick (strength 1800 lbs.)	1 : 3 Portland	175
Common brick (strength 1800 lbs.)	1 : 3 Natural	150
Common brick (strength 1800 lbs.)	1 Portland, 1 lime, 3 sand	125
Common brick (strength 1800 lbs.)	1 : 3 lime	100

PART II

THE FERROUS METALS

CHAPTER XI

PIG IRON

GENERAL

280. Historical. The ferrous metals comprise only three general classes of material, cast iron, wrought iron and steel. All of these are derivatives of iron, produced artificially by the reduction of iron ores and subsequent treatment by various metallurgical processes of the pig iron which is directly produced from ores. Cast iron, wrought iron, and steel are distinctly different materials, judged by their comparative physical properties, in spite of the fact that metallic iron is present in all to the extent of at least 92 per cent.

The production of iron and steel from ores and the fabrication of useful implements therefrom comprises one of the oldest mechanic arts known to man.

Ores of iron are all essentially oxides of iron, adulterated with large or small amounts of earthy material. Thousands of years ago it was discovered that metallic iron could be produced by heating iron ore in charcoal fires, the oxygen being removed by the charcoal, leaving metallic iron in a pasty condition. The primitive method of burning ore in heaps over a charcoal fire gradually developed into the Catalan forge process, by which wrought iron and, more rarely, steel was produced in all parts of the world for many centuries.

The Catalan forge in its early form was nothing more than a hole in the ground lined with masonry. This was filled with charcoal and ore, either mixed or deposited in vertical layers, and an air blast, delivered through a downward inclined tuyere which projected into the mass, supplied the necessary oxygen for combustion of the fuel.

The temperature acquired is not sufficient to melt the iron, but will fuse the slag, which may then be tapped off, and the iron is withdrawn as a pasty mass. If the tuyere be given a lesser incline and the process be continued for a longer time, the temperature attained is sufficient to promote the combination of a certain amount of carbon of the fuel with iron, thereby producing steel.

Cast iron was never produced in the Catalan forge or other early form of device for reducing iron from the ore, because the temperature attained was never sufficient to melt the iron and effect the combination of iron with the 3 or 4 per cent of carbon which is primarily responsible for the structural and physical characteristics which distinguish cast iron from wrought iron and steels.

Cast iron, or more properly speaking, pig iron (pig iron is commonly called cast iron after being remelted and cast in molds) was not produced until the blast furnace process of ore reduction was developed in comparatively modern times.

281. Iron and Steel in Construction. From the standpoint of the economist the iron and steel industry is by far the most important and valuable one in existence. The world's production of iron and steel represents a greater proportion of our manufacturing wealth than that of any other industry, and probably no other factor has contributed so much to the development of all arts and industries which has characterized the last fifty years as has the progress made in the manufacture of better and cheaper iron and steel.

Cast iron is made so easily by a simple process of remelting pig iron and casting in molds, that it is produced in practically every city of industrial importance in the civilized world. Its strictly structural uses are somewhat limited, owing to the greater adaptability of wrought iron and steel to structural needs. As a material of construction in general, however, and especially as a material for use in construction of machines, implements, etc., it finds countless applications which cannot be as cheaply and satisfactorily served by any other material.

Wrought iron has, since the earliest times, been an important material in many arts and industries. Until the development of cheap methods of steel making in the latter half of the nineteenth century, it was the principal metallic structural material. Even now it has many uses in fields which steels have not been able to invade, in spite of the fact that the latter may be more cheaply produced.

Steel assumed its present place as the most important metal for general construction purposes with the development of the Bessemer process of steel making following its invention in 1855. Prior to this time steels had been produced only by comparatively slow and expensive methods, which made impossible any real competition with the relatively cheap wrought iron. In recent years open-hearth process steel has been gradually replacing Bessemer steel in many fields, but the quantity of both used structurally, and in construction generally, remains enormous. (In 1913 over 31,000,000 long tons of steel were produced in the United States alone.)

Pig iron has no construction uses, but is the raw form of iron from which wrought iron and steels as well as cast iron are made.

282. General Classification of Iron and Steel. In a later chapter a technical classification of iron and steel will be introduced. For present purposes, however, iron products will be grouped under the following heads:

(1) *Pig iron,* the product obtained by the reduction of iron ores in the blast furnace. Carbon is present in amounts not usually below 2.5 per cent nor above 4.5 per cent. It is cast as it flows directly from the blast furnace into rough bars called " pigs."

(2) *Cast iron,* remelted pig iron after being cast or about to be cast in final form. It does not necessarily differ from the pig in composition, and is regarded by the metallurgist as the same thing as pig iron. It is not malleable at any temperature.

(3) *Malleable cast iron,* a form of cast iron which by a special annealing treatment after casting in final form has been rendered malleable or semi-malleable.

(4) *Wrought iron,* a form of iron which is aggregated from pasty particles without subsequent fusion. Wrought iron contains slag enclosures, and is initially malleable, but normally possesses so little carbon that it will not harden when rapidly cooled.

(5) *Steel,* iron which has been cast from a molten mass, whose composition is such that it is malleable at least in some one range of temperature, and which may or may not harden upon sudden cooling. Steel which owes its distinctive properties chiefly to carbon is called *carbon steel.* Steels whose distinctive properties are due chiefly to the presence of elements other than carbon are called *alloy steels.*

THE RAW MATERIALS OF THE IRON INDUSTRY

ORES OF IRON

283. General. Ores of iron consist essentially of compounds of iron, usually oxides, mixed with " gangue " (silica, clay, calcic phosphates, etc.), and those of commercial importance contain from 25 to 70 per cent metallic iron (usually 40 to 60 per cent).

Iron is extracted from ores by a process known as " smelting," which consists primarily in the heating of the ore to a high temperature under strongly reducing conditions in the presence of a basic flux. The reducing agent serves to remove the oxygen from the oxides of iron, leaving metallic iron together with such elements as carbon, silicon, manganese, phosphorus, and sulphur, which are invariably present either in the ore or in the fuel used in melting. The flux, usually limestone, combines with the gangue of the ore and the ash of the fuel, producing a fusible slag which may be separated from the metallic iron. The forms of iron ore of greatest commercial importance are *hematite, limonite, magnetite,* and *iron carbonate.*

284. Hematite. Hematite, sometimes called "red hematite" or "red iron ore," is anhydrous ferric oxide, Fe_2O_3, containing when pure 70 per cent iron. It occurs usually in granular or massive structure, although it sometimes has a columnar formation or a brilliant scaly structure, when it is called "specular hematite." It is usually very hard and heavy, varies from black to brick red in color and often occurs as an earthy ore which is cheaply handled. An oölitic form of hematite occurs in enormous quantities in France, Lothringen, and Luxemburg. This contains only 30 to 35 per cent iron, but, owing to its lime content, is partly or wholly "self-fluxing." This ore is the basis of the great German, French and Belgian iron industries. Hematite is almost entirely non-magnetic, and when pure is almost identical in appearance and composition with ordinary deep-red iron rust.

285. Limonite. Limonite, also called "brown iron ore," or "bog iron ore," is hydrated ferric oxide, $Fe_2O_3+[n]H_2O$, containing about 60 per cent iron. It differs in composition from red hematite only in that it contains about 14.5 per cent chemically combined water. It is softer than red hematite, lighter, and occurs usually in massive form. A familiar form of limonite is the newly formed fresh yellow rust on iron.

286. Magnetite. Magnetite is the magnetic oxide of iron, Fe_3O_4, containing when pure 72.4 per cent iron. It is a hard black mineral occurring in granulated or massive structure. It is almost as magnetic as pure iron, very heavy, and often (in U. S.) contaminated with silica, titanium, and phosphorus. It is identical in composition with the black mill scale which forms on iron at temperatures above redness.

287. Iron Carbonate. Iron carbonate, commonly called "siderite" or "spathic iron ore," $FeCO_3$, contains when pure 48.3 per cent iron.

It changes to limonite and hematite on weathering. It is rarely used as an ore in its raw state, but is subjected to a preliminary calcination to remove the CO_2.

288. Extent of Ore Production in the United States. The great bulk of the hematite ore used in the United States comes from the Lake Superior district (Michigan, Minnesota, and Wisconsin), or from Alabama.

Of the total amount of hematite produced in 1913 the Lake Superior district produced over 52,000,000 long tons, while Alabama produced about 4,000,000 long tons, and no other district produced over about 500,000 tons. The total production of hematite in 1913 was 58,018,295 long tons.

The production of limonite in 1913 was 1,577,019 long tons, of which Alabama produced about 845,000 tons, Virginia about 354,000 tons, Tennessee about 125,000 tons and Georgia about 96,000 tons. No other district produced over 30,000 tons.

The production of magnetite in 1913 was 2,357,274 tons, the bulk of which was produced by New York, New Jersey, and Pennsylvania. The total production of carbonate was 27,849 tons, Ohio being the largest producer.

It appears therefore that hematite constitutes about 93.6 per cent of the country's ore production, limonite about 2.5 per cent, magnetite about 3.8 per cent, and carbonate only 0.05 per cent. The Lake Superior district's output of hematite alone amounts to more than 84 per cent of the entire tonnage of iron ore mined in the United States.

289. Ore Mining and Transportation. The manner of mining adopted depends to a great extent upon the physical condition of the ores. Many of the ranges of hematite ore in the Lake Superior district, notably, the famous Mesabi range, which produces two-thirds of the Lake Superior ore, produce ores so soft and finely divided that they are very easily and cheaply worked by steam shovels. Others in the same district, however, are hard and dense, and must therefore be drilled and blasted. These rock ores are more expensively mined than the soft ores, but, as we shall later see, the use of a certain proportion of rock ore with the earthy ore is indispensable to the successful operation of the blast furnace.

The limonites are always rather soft; the magnetites, on the other hand, are usually very hard and dense and are necessarily mined or quarried by the use of explosives and crushed before smelting.

Ores commonly require long transportation in order that the smelting may be done in a district of cheap fuel. Since, as above noted, the Lake Superior district supplies over 84 per cent of all the ore smelted in the United States, the problem is largely a question of the delivery of Lake Superior ores to the coal regions of Pennsylvania, Ohio, Illinois, and New York. These four States produce, therefore, about 81 per cent of the country's output of pig iron. (Pennsylvania produces about 42 per cent, Ohio 23 per cent, Illinois about 9.5 per cent, and New York over 6.5 per cent.)

No local smelting of the Lake Superior ores has been done in the past, but the recent construction of furnaces in the ore district gives promise of a change in this regard in the near future. The ores have always been transported practically exclusively by the ore boats of the Great Lakes. These boats (10,000 to 15,000 tons capacity), are loaded at Lake Superior ports in a very few moments, elaborate loading devices being used. Passing through the locks of the Sault Ste. Marie canal, the boats proceed either to Chicago by way of Lake Michigan, or to the ports of Pennsylvania, Ohio and New York by way of Lakes Huron, St. Clair, and Erie. Discharging is accomplished in a period of from four to six hours by the use of mechanical unloading devices.

The ores of Alabama, which constitute the only other important deposits, are mostly smelted in the neighborhood of the mines.

290. Special Preliminary Treatment of Ores. Practically all of the hematite, and therefore the greater proportion of all ores used, is charged into the furnace without any preliminary treatment. Some ores, however, behave more satisfactorily in the furnace after having been subjected to one or the other of the following preliminary processes.

Calcination is resorted to for the purpose of removing water from limonites or hydrous ores; removing CO_2 from carbonates; oxidizing a portion of the gangue of dense ores, particularly magnetites, thereby rendering them more accessible to the furnace gases; or, lastly, rendering the ore magnetic to facilitate subsequent magnetic concentration. The calcination is usually accomplished in vertical furnaces resembling a mixed feed type lime kiln. The fuel is charged with the ore at the top and the temperature is controlled by regulation of the air supply.

Roasting is resorted to solely for the purpose of removing sulphur from ores. The sulphur is present as pyrite, FeS_2, which is decomposed at a moderate heat, liberating S and FeS. The FeS is oxidized by air to form ferrous sulphate, $FeSO_4$, and further heating decomposes the sulphate, forming ferric oxide, Fe_2O_3, with the liberation of sulphur dioxide and oxygen, thus:

$$FeS_2+\text{Heat}=FeS+S;$$

$$FeS+2O_2=FeSO_4;$$

$$2FeSO_4+\text{Heat}=Fe_2O_3+2SO_2+O.$$

Roasting is accomplished either in large cylindrical kilns (20 feet in diameter by 30 feet high), the fuel being mixed and charged with the ore at the top (Fig. 143) or in a gas-fired kiln which consists of an annular brick-lined chamber surrounding a central cylindrical flue (Fig. 144). Gas is burned in a separate combustion chamber and the products of combustion are drawn through the ore into the central flue.

Concentration of ores is employed occasionally for the purpose of freeing the ore of a part of the gangue, and for enriching the ore before smelting. *Wet concentration* is sometimes used to remove clay, loam, etc., by a simple process of washing. Another method of wet concentration is by the use of jigs which separate pebbles and sand from the ore by agitation of perforated trays set in tanks of water.

Dry concentration is usually accomplished by some type of magnetic separator. If the ore is not already magnetic it is magnetized by preliminary calcination. It is then crushed and passed in a thin layer before strong magnets, the magnetic portion being thus attracted away from the non-magnetic. Fig. 145 shows one type of magnetic concentrator. The crushed ore is fed on to belt B and carried between the poles of a powerful electromagnet where the magnetic portion is attracted to the cross belts B', which are provided with a coating of magnetic material. The cross belts carry the metal to one side out of the magnetic field, when it drops into the hoppers provided below. The tailings remain on belt B and are discharged into a bin when the belt passes over a sheave.

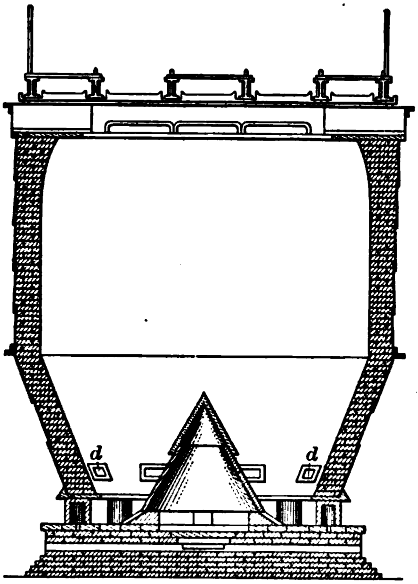

FIG. 143.
Coal-fired Kiln for Ore Roasting.

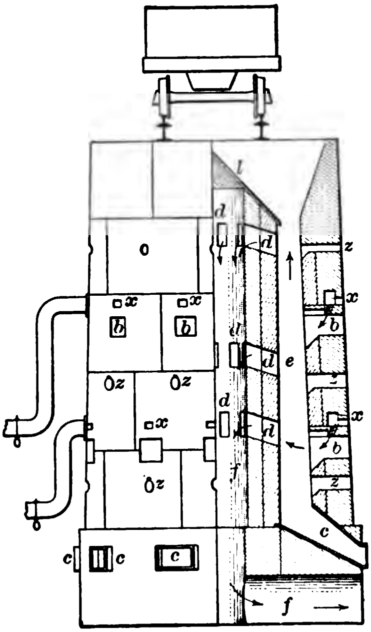

FIG. 144.
Gas-fired Kiln for Ore Roasting.

291. Grades of Ore. Ores of iron are divided into two main classes known as *Bessemer ores* and *non-Bessemer ores.* This division is due to the fact that acid Bessemer steel must contain less than 0.1 per cent phosphorus, and neither the blast furnace reduction of the ore nor the acid Bessemer steel process is able to reduce the phosphorus content. All ores in which the phosphorus content does not exceed one-thousandth part of the iron content are therefore classed as Bessemer ores, and all ores carrying a higher percentage of phosphorus as non-Bessemer ores. The Bessemer ores are worth about 15 per cent more in the market than non-Bessemer ores.

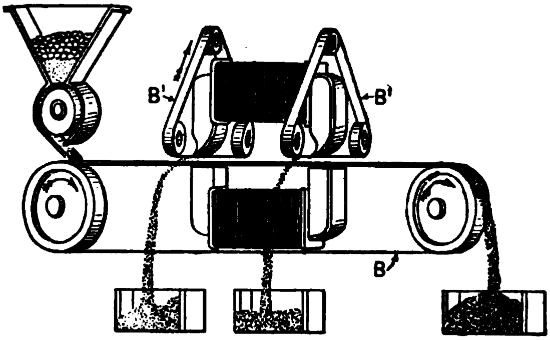

FIG. 145.
Type of Magnetic Separator for Ore Concentration.

THE FLUX

292. Necessity for Use of Flux. The office of the flux, as has been stated above, is to render fusible the more or less infusible gangue of the ore and provide a fusible slag in which the non-metallic portion of the ore may be carried off. The exact character and amount of the flux needed will depend upon the composition of the ore and fuel used, and the character of pig iron required. In general it may be said that a basic flux is required for acid gangues (high in silica, alumina, etc.), while an acid flux might be required were the gangue basic (high in lime, magnesia, or alkaline matter). As a rule gangues are acid in character and fluxes are almost invariably basic in character.

The flux serves another purpose, as will be later shown, besides taking care of the acid gangue and ash. The sulphur in the charge, whether in the ore or in the fuel, combines with the lime of the flux, forming calcic sulphide, which is removed in the slag.

293. Fluxes Used. The cheapest form of basic flux is limestone, and hence it is almost invariably used. The use of quicklime, CaO, would seem to be advantageous, but it is found that the advantage gained in the operation of the blast furnace is offset by the additional cost of calcination of the limestone. Occasionally $CaCO_3$ in the form of oyster shells is used as a flux in place of limestone. Limestone used as a flux should be very pure, since the presence of acid impurities greatly impairs its efficiency in fluxing the silica, alumina, etc., in the gangue. At least 95 per cent pure $CaCO_3$ is desirable.

Pure or high calcium limestones are not always available, and magnesian or dolomitic limestones are sometimes used. The replacement of a considerable part of the calcium by magnesium does not appear to appreciably impair the efficiency of the flux and, in fact, several authorities claim an advantage in the use of magnesian limestone.

The Fuel

294. General. The fuel used in a blast furnace must serve as a reducing agent as well as a source of heat. The fuel requirements from the standpoint of heat required always exceed the requirements for reduction, however, and therefore only its thermal value need be considered in this connection.

The rapidity of melting attained in the furnace is dependent upon the rapidity of heat production, which, in turn, is dependent upon the rapidity of oxidation of the carbon of the fuel by the oxygen of the air. It is therefore desirable that a fuel, in addition to having a high calorific value, have a porous rather than a dense structure, thereby affording additional surface to the action of the oxygen. It is further necessary that it possess sufficient firmness while being heated so that it will not fill up the interstices of the charge, thereby impeding the flow of the gases.

All solid fuels consist of a combustible portion, carbon and hydrocarbons, which combine with oxygen to form gases, and an incombustible portion which remains as a solid residue called ash, which is insoluble and must be fluxed from the furnace.

Three classes of solid fuel have been used in the blast furnace; raw coal, coke, and charcoal. From the standpoint of structure and accessibility to oxidation charcoal surpasses coke and coke surpasses coal. From the standpoint of firmness coke stands first and charcoal is least desirable. Most of the hard, well-made cokes withstand the pressure of the charge very well, although coke is a rather friable material. Bituminous coals absolutely melt down during heating, and anthracites under similar circumstances are apt to splinter into fine particles.

Charcoal is the purest of the solid fuels and has the least ash. Anthracite coal is less pure than charcoal and has much more ash; it is, however, much purer than coke and has very much less ash.

Each type of fuel therefore has its decided advantages and all are being used, the choice in a particular locality being dependent mainly upon relative cost.

between the retorts are thereby heated to a high degree and the heat retained tends to equalize the temperature in the retort at the beginning and end of the process.

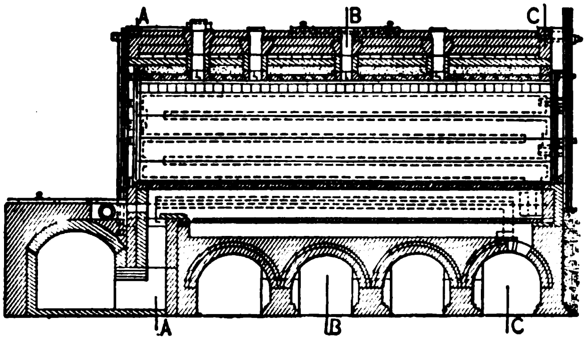

Fig. 147*a*.—Semet-Solvay Retort Coke Oven. Longitudinal Section.

A charge of 4½ tons is coked in eighteen to twenty-six hours. The retort is charged by overhead mechanical devices, and the coke is discharged by a mechanical pusher which forces the entire retortful of coke out bodily. The water cooling is done outside the retort.

The distillation begins at the retort walls and proceeds inward, the gas escaping at the median plane of the mass, thereby causing a cleavage plane which makes the length of the coke after splitting only one-half the width of the retort. The products of distillation are conveyed by a collecting pipe to the condensing plant where they are relieved of the tar, ammonia, etc. The yield per ton of Pittsburgh coal is about 1300 pounds of coke, 5000 cubic feet of gas, 75 pounds of tar, and 20 pounds of ammonic sulphate.

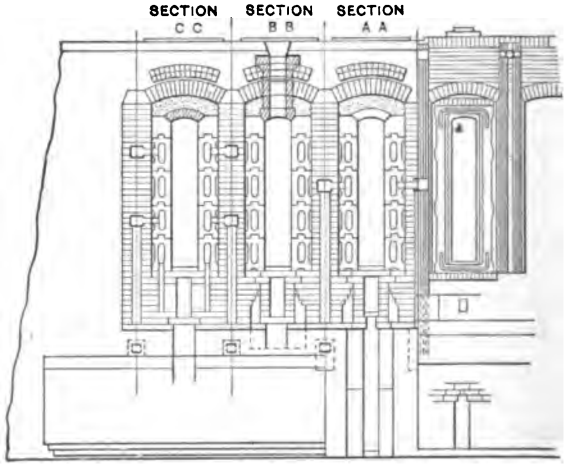

Fig. 147*b*.—Semet-Solvay Retort Coke Oven. Transverse Sections.

The Otto-Hoffman retort oven (Figs. 148 149), aside from construction details, differs from the Semet-Solvay retort principally in that provision is made for using a part of the heat of the escaping products of distillation to heat the incoming gas and air which are mixed and burned in the flues surrounding the retorts. The retorts are about 33 feet long, 6 feet high, and 16 to 24 inches wide, and are arranged in batteries of about fifty. The intervening walls are 12 inches thick and contain the flues in which the gases are burned. For this purpose about one-half the purified gas from the retorts is used.

The operation of the furnace involves the regenerative principle. The escaping hot products of combustion in the flues are led through chambers (Fig. 148) in which brick are piled to form a loose checkerwork. In their passage they heat up the brickwork of the regenerative chamber before passing on to the stack. After a definite interval of time the course of the escaping burned gases is diverted to a second set of regenerative chambers. The air and gas which are to be used in heating the retorts are now admitted through the flues beneath the hot regenerative chambers and in passing up through the hot checkerwork become heated to about 1100° C. before reaching the flues where they are burned. The direction of circulation of the gases through the flues is reversed at frequent intervals so that one set of regenerators is always being heated by the burned gases while the second set is performing its function of pre-

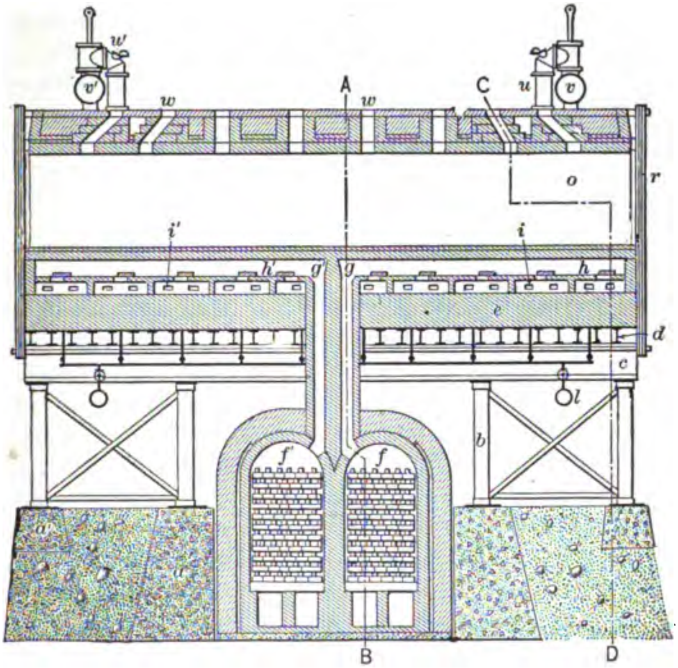

Fig. 148.—Otto-Hoffman Retort Coke Oven. Longitudinal Section.

heating the incoming gas and air. An increased heat efficiency is thus obtained.

A 7-ton charge is coked in from twenty-four to thirty-six hours, the charging and discharging, and also the condensing of the products of distillation being accomplished in a manner similar to that used in the Semet-Solvay process.

299. Charcoal Manufacture. Charcoal was at one time commonly made by burning in heaps without recovery of the by-products. The volatile constituents of wood are much higher than is the case with coal, however, and the waste in charcoal-making is therefore much greater than in coke-making. This fact largely accounts for the early adoption of kilns and closed retorts in charcoal-making. Most of the charcoal now made is burned in by-product retorts with recovery of wood alcohol, acetic acid, tar, gas, etc.

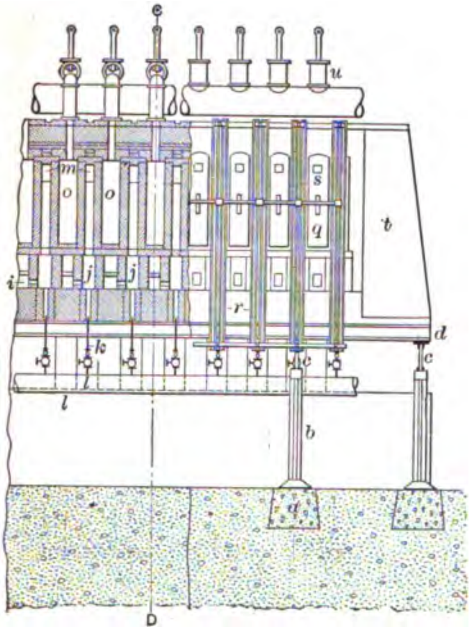

FIG. 149.—Otto-Hoffman Retort Coke Oven. Transverse Sections.

As a type of the modern retort charcoal plant, that of the Algoma Steel Company at Sault Ste. Marie is here described. The retorts are horizontal shells, 46 feet long, $6\frac{1}{4}$ feet wide, and $8\frac{1}{3}$ feet high, built of boiler plate and fitted with air-tight end doors. The shells are set in brickwork like boilers, and fireboxes are provided at either end. The flues lead along the walls so as to heat the retort evenly. The wood (usually pine, ash, spruce, birch, willow, fir, or alder) is split, seasoned, loaded on trucks, and run into the retort where it is subjected to heat at the temperature of carbonization for from eighteen to twenty hours. The cars are then pushed into an exactly similar retort, which is not fired, allowed to cool for twenty-four hours, and then to a second similar cooler for another twenty-four hours, after which the charcoal is ready for the blast furnace. The products of distillation are led by a collecting pipe to the by-product plant where the gas, alcohol, acetic acid, and, later, the wood-creosotes, heavy oils, and tars are successively recovered. The gas is usually used under boilers to generate steam for the operation of the power plant.

300. Relative Use of Different Fuels. The relative extent to which the different fuels above discussed are used in the production of pig iron is indicated from the following data abstracted from "Mineral Resources of the United States," 1913.

Bituminous fuel, chiefly coke, was used in the production of about 30,326,000 tons of pig iron, or 97.9 per cent of the total.

Anthracite fuel and coke was used in the production of about 278,000 tons of pig iron, or 0.9 per cent of the total.

Anthracite alone was used in the production of about 22,000 tons of pig iron, or 0.07 per cent of the total.

Charcoal was used in the production of about 340,000 tons of pig iron, or 1.1 per cent of the total.

THE REDUCTION OF IRON ORES

Manufacture of Pig Iron

301. General. Practically all of the iron used commercially in the world to-day, whether it be used as cast iron, wrought iron, or steel, is first reduced from the ores in a blast furnace to form pig iron. Many direct processes, by which wrought iron and steel may be made directly from the ore, have existed for ages, but their present importance is only an historical one.

The first statement above made means, in effect, that all the iron which is used in the manufacture of wrought iron and steels has had an excessive amount of carbon and silicon added in the smelting process, necessitating their subsequent removal at great expense. Nevertheless, the blast furnace process has been so perfected and cheapened that no direct process can compete with it in any degree.

302. The Blast Furnace Process in General. "The process of smelting iron in the blast furnace consists essentially of charging a mixture of fuel, ore, and flux into the top of the furnace, and simultaneously blowing in a current of air at the bottom. The air burns the fuel, forming heat for the chemical reactions, and for melting the products; the gases formed by this combustion remove the oxygen from the ore, thereby reducing it to metallic form; and the flux renders fluid the earthy materials. The gaseous products of the operation pass out at the top of the furnace, while the liquid products, cast iron and slag, are tapped off at the bottom. The escaping gases are combustible, and therefore are conducted through pipes to boilers and stoves, where they perform the useful service of heating the blast and raising steam or operating internal combustion engines." *

The essential equipment of a smeltery consists of the blast furnace itself, the equipment for handling the charges and other equipment for handling the products, stoves which preheat the air used for the blast, and blowing engines which supply air under pressure and deliver it to the furnace.

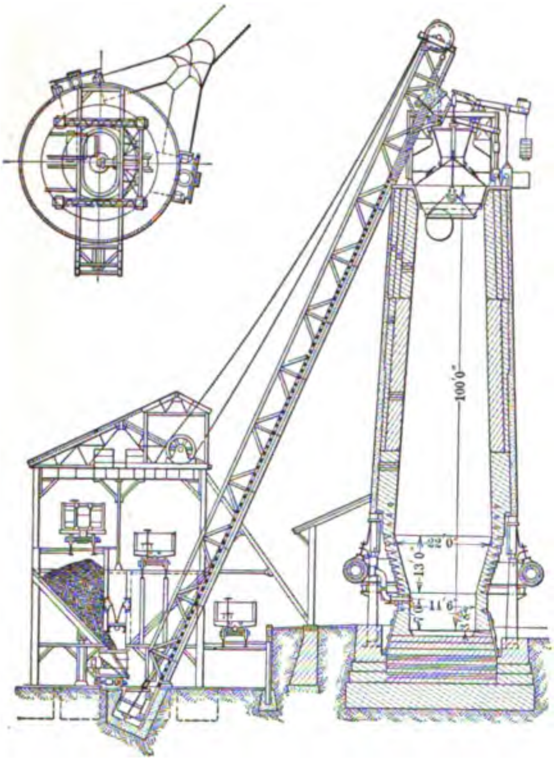

FIG. 150.—Blast Furnace and Charging Mechanism. (Campbell.)

303. The Blast Furnace and its Mechanical Equipment. The blast furnace (Fig. 150) consists of a vertical shaft built of steel and lined with firebrick. The lower portion, called the " hearth " or " crucible," is cylindrical, about 8 feet high, and 15 to 17 feet in diameter. It contains the " tuyeres," the " cinder notch," and the " iron notch," and serves as a crucible in which the molten products of the operation are collected. Above the hearth the walls diverge, forming an inverted truncated cone called the " bosh," which is 12 to 13 feet high and 22 to 24 feet in diameter at the widest point. Above the bosh extends the " stack," converging to a diameter of about 16 to 18 feet at the " throat " at a height of 45 to 60 feet above the bosh.

The shell of the shaft above the bosh is so constructed as to be independent of the parts below. It is supported by a steel ring called the " mantle, " resting upon columns. The walls of the shaft portion of the furnace, called the " inwalls," have a lining, usually 27 inches thick, of hard, high-silica, fireclay brick designed to resist abrasion. The lining of the bosh is also 27 inches thick, except when the bosh is surface-cooled, in which case a 9- or 13½-inch lining is used. The lining of the hearth usually increases

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* Forsythe, "The Blast Furnace and the Manufacture of Pig Iron," p. 90.

in thickness downward, being more than 30 inches thick at the bottom. A more refractory but softer fireclay brick is used in the lining of the bosh and hearth.

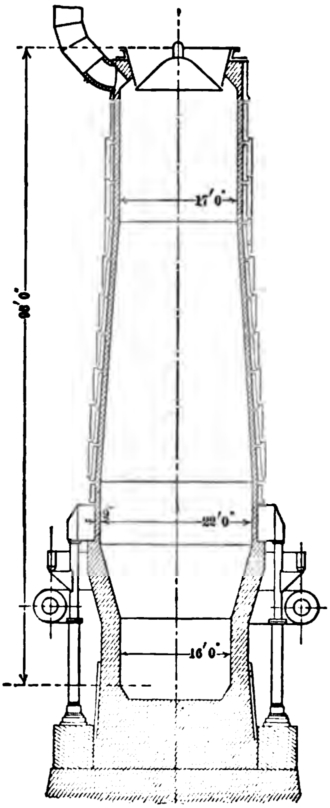
The ring of " tuyeres " pierce the hearth lining just below the bosh. These are 8 to 16 pipes having an internal diameter of from 4 to 7 inches, through which the hot blast of air is driven. Both the tuyeres and the tuyere-blocks are protected from burning by being made of hollow metal construction and cooled by water circulating through them.

The hole for tapping off the liquid slag, called the " cinder notch," is located on the side of the hearth about 3 feet below the tuyeres. This also is protected by a water-cooled casting. It is closed by stopping up the hole by an iron bar having an enlarged end, until the slag itself has solidified and plugged the hole.

The " iron notch " or " tap-hole," used for tapping out the molten iron, is located at the very bottom of the hearth in the front or " breast " of the furnace. It is commonly stopped by ramming in several balls of clay.

The hottest part of the furnace, the bosh, is cooled in one of two ways: The older method involves the use of thick walls in which wedge-shaped hollow castings are inserted. These " cooling plates " are provided with inlet and outlet pipes and are kept full of circulating water. They are so placed as to form a series of rings from 1 to 2 feet apart vertically. The second method consists of " surface-cooling " of the bosh walls, which in this case are not over 13½ inches thick. The cooling is accomplished either by sprays of water directed against the bosh jacket from all sides, or by a spiral trough winding about the boshes and kept full of running water.

A late modification of the blast furnace consists in the application of surface cooling to the entire stack of the furnace. This necessitates the use of a thin lining of the " inwalls," usually 12 inches. Both the spiral trough and the spray method of cooling are used. Fig. 151 shows a furnace modified from the old form to permit water cooling and thin lining.



SECTION OF THIN LINED BLAST FURNACE

FIG. 151.—New Thin-lined Water-cooled Blast Furnace.

The increase in sectional area as the material sinks below the level of the stock line allows for the natural expansion at the higher temperature, and tends to prevent clogging. The reduction in the bosh holds up the material until the fuel is burnt out, and the liquid iron and slag gradually drop into the hearth, where their difference in specific gravity causes them to separate, permitting them to be tapped out separately.

The combustible gases generated during smelting are taken from the furnace just below the bell through outlets, one to four in number, which converge into a single large pipe called the "down-take." An auxiliary pipe connected with the gas outlet pipes, and provided with a valve called the "bleeder," serves as an emergency relief at times of unusual gas pressure.

Near the lower end of the down-take the "dust-catcher" is placed. This is simply an enlargement of the pipe designed to remove solid particles carried over into the down-take by reason of the velocity of the current of gases. Since this velocity is reduced in proportion to the square of the diameter of the conveying pipe, the great reduction in velocity as the gases pass the dust-catcher allows by far the greater part of the suspended particles to settle by gravity. The gas can now be used under boilers or in hot-blast stoves, but cannot be used in internal combustion engines without having first been cleansed in some type of washing device wherein all suspended matter is removed by water. In American practice two long rows of storage bins behind the blast furnaces are kept filled with ore by bottom-dump cars or a conveying device. Between and under the bins runs a track upon which "ore larries" are switched back and forth containing in succession weighed amounts of ore, flux and fuel. These cars discharge into the loading skip of the blast furnace.

The amount of material that must be charged into the top of a large blast furnace every twenty-four hours exceeds 2000 tons, and charging goes on twenty-four hours in the day the year round with never more than a few hours' stop except in the case of serious accident.

The charging is accomplished by means of a long double inclined skipway, the mechanism of which is controlled from the ground level. The skips are loaded by gravity from the larries, elevated to the top of the furnace, and discharged into the hopper automatically.

The upper hopper of the furnace is closed at the bottom by an inverted iron cone called the "bell." The counter-weight which holds the bell in place is controlled by the motion of a piston in a steam cylinder. By lowering the bell the contents of the upper hopper are allowed to fall into the hopper proper of the furnace. This larger hopper is also closed by a bell controlled in the same manner from the ground level. At intervals the bell is lowered and the contents of the hopper are distributed in an even layer upon the material already in the furnace. At this time the upper hopper is closed so that there is never a direct opening from the interior to the open air. Sometimes elaborate devices are installed to insure an even distribution of the charge as it falls into the furnace, avoiding the segregation of the fine and coarse material that is apt to be caused by the ordinary bell.

304. Hot-blast Stoves. Each furnace is connected with from three to five hot-blast stoves (most commonly four). The design of the stove varies, but the same principles govern the operation of all, so that only one of the type most commonly used, the Julian Kennedy modification of the Cowper stove, will be here described.

The stove consists of a vertical steel cylinder, 20 to 22 feet in diameter and 80 to 110 feet high, containing two firebrick chambers (Fig. 152). The central chamber is open, while the outer annular chamber is divided into a large number of small flues. Gas from the blast furnace and a definite proportion of air are admitted at the bottom of the open chamber and burned. The products of combustion rise to the top of the furnace and pass downward through the small flues and thence to the stack. The greater part of their heat is taken up by the brickwork of the flues. After burning gas in a stove for about three hours the latter is hot enough to heat the blast.

Air from the blowing engines is now admitted at the bottom of the small flues in the outer chamber and passes upward, taking up the heat stored in the brickwork. Thence it passes downward through the central flue to the furnace. The blast temperature (425 to 650° C.), is kept fairly uniform by working about four stoves per furnace, keeping three always "on gas" while the fourth is "on air," and changing stoves about once an hour. The waste gases from the blast furnace amount to about 90,000 cubic feet per minute at a temperature of about 235° C. One-third of this amount, or about 30,000 cubic feet per minute, is required to heat the three stoves "on gas," and the balance is available for power purposes.

305. The Blowing Engines. The air for smelting is delivered under pressure by immense blowing engines, the largest of which develop from 2000 to 2500 horse-power, and will deliver from 45,000 to 65,000 cubic feet of air per minute at a pressure of from 15 to 30 pounds per square inch. The above capacity just about suffices for one large blast furnace. The blowing engines have in the past been steam driven; an important change in the last few years, however, has been the introduction of internal combustion engines which utilize the gas from the blast furnace after washing.

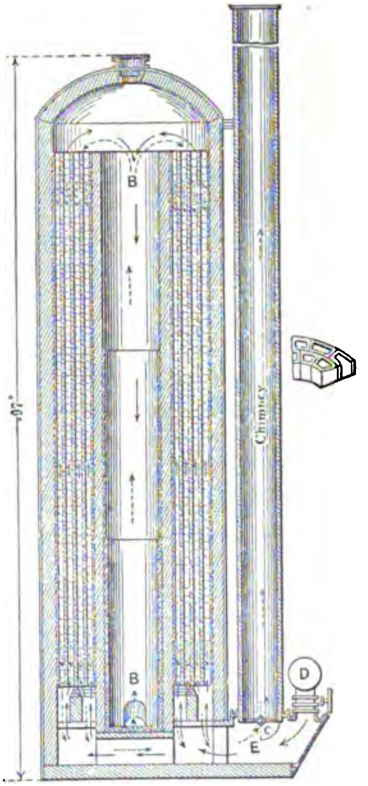


Fig. 152.—Hot Blast Stove. Vertical Section.

306. Drying the Blast.

The presence of a variable amount of moisture in the air of the blast, sometimes amounting to as much as 1 pound per 1000 cubic foot of air, means an expenditure of a great amount for fuel which serves no purpose other than dissociating the water vapor. (The fuel consumed in dissociating 1 pound of moisture per 1000 cubic feet of air will amount in one day to about 25 tons of coke.) The dissociation of the air to free hydrogen and oxygen in the smelting zone therefore results in materially cooling that zone. The hydrogen and oxygen will recombine to form water vapor again, with the evolution of a corresponding amount of heat, in the upper part of the furnace, but this does not compensate for the loss of heat in the smelting zone, where it is most needed.

For these reasons most furnaces have now been equipped with refrigerating devices whereby the air is cooled far below its dew-point, and its moisture largely reduced by condensation before being drawn into the blowing engines.

The method of blast desiccation first introduced by James Gayley in 1904 consists in drawing the air through chambers containing coils of pipe through which a cold solution of calcium chloride is circulated. The heat of the air is transferred to the brine, and as its temperature is lowered its capacity for carrying moisture is reduced and the precipitated moisture is deposited on the pipes as frost. The pipes are freed from the frost by sprays of water about once in four days.

The calcium chloride solution or brine is cooled to the necessary degree by an ammonia refrigeration plant. The principles governing the operation of such a plant may be briefly summarized as follows:

Ammonia, (NH_3), is one of the compounds which, although a gas at ordinary atmospheric temperatures and pressures, may be liquefied by sufficiently reducing the temperature or by subjecting it to heavy pressure at ordinary temperatures. Having once been liquefied under pressure, it will therefore take up heat (latent heat) if the pressure is relieved, thus permitting it to reassume the gaseous state. Any material may therefore be cooled to a great degree if it be so placed that its heat may be absorbed by ammonia while the latter is passing through the transition from a liquid to a gas.

In practice the ammonia is first subjected to heavy pressure in large compressors and then conveyed to condensers where the heat derived from the compressor cylinders is removed and the gas liquefied. The usual type of condensers used consists of coils of 2-inch pipe with 1¼-inch pipes passing through them. The gas under pressure passes through the outer pipes while cooling water is circulated through the inner pipes in the opposite direction. The gas is thus sufficiently cooled to become liquid at the existing pressure and is conveyed as a liquid under pressure to the coolers.

The coolers again consist of large pipes within which smaller pipes are placed. The brine is circulated through the inner pipes while the liquid ammonia is admitted to the outer pipes. The sudden increase in the size of the container relieves the pressure on the ammonia, causing it to reassume the gaseous state with the absorption of heat of vaporization from the brine in the adjoining container. The ammonia gas is now reconveyed to the compressors, while the cold brine passes to the coils over which the air passes on its way to the blowing engines.

The saving effected by the use of dry blast is two-fold: the saving of fuel used per ton of iron produced, and the saving caused by increased uniformity in furnace operation and consequent increased uniformity of the product. The saving in fuel has been estimated to be about 20 per cent with the same output of iron, or 12½ per cent saving in fuel with an increase of 10 per cent in the iron output. The saving due to increased uniformity in operating conditions is due to the fact that a cubic foot of dry air will always weigh the same and provide practically the same amount of oxygen to burn the fuel, while a cubic foot of atmospheric air will vary in weight and oxygen content if it varies in moisture content.

THE FUNCTIONS OF THE BLAST FURNACE

307. General. The blast furnace has five distinct duties to perform:

(1) It must deoxidize the iron ore;
(2) It must carburize the iron;
(3) It must melt the iron;
(4) It must render fusible and melt the slag, and
(5) It must separate the molten iron and the slag.

308. Deoxidation of the Iron Ore. The deoxidation of the iron ore is of course the primary object of smelting. The recovery of iron would be impossible without deoxidation, because of the operation of the general principle upon which most metallurgical operations are fundamentally based, i.e., that oxidized bodies in a state of fusion will not unite with unoxidized ones. The application of this principle to the metallurgical processes in iron- and steel-making may be otherwise stated as follows:

First, when an element such as carbon, silicon, or phosphorus, existing in chemical union with a metal, combines chemically with oxygen, the resulting oxidized product must, when melted, separate itself from the remaining metallic portion; and

Second, if oxidized metal parts with its oxygen, i.e., becomes deoxidized or reduced to the metallic state, the newly liberated portion joins the metal in the furnace.

If, therefore, the iron were not reduced, the iron oxide would not be recovered, but would be lost with the slag.

A second essential result of the deoxidation of the iron is the fact that the immunity of the firebrick lining of the furnace from rapid destruction by the corrosive action of the slag is due to the deposition of free carbon on the walls during the process of smelting, and, if the slag contained any large amount of iron oxide, this iron oxide would oxidize and remove the carbon coating, leaving the brickwork unprotected against the destructive attack of the slag.

309. Carburization of the Iron. Carburization of the iron is essential because at the temperature attained in at least the greater part of the melting zone it would be impossible to render molten free iron, whereas iron saturated with carbon is sufficiently superheated beyond its melting-point to make it very fluid, so that it easily becomes separated from the slag in the hearth.

310. Melting the Iron. Since, as has been indicated in Art. 308, when fusion takes place all oxidized bodies unite to form the slag and expel therefrom all fused unoxidized bodies, it is essential that the iron be fused in order that it may be expelled from the slag just as oil is rejected by water. The molten iron will necessarily absorb all deoxidized substances such as silicon, manganese and phosphorus, which exist as free metals or metalloids in the lower portion of the furnace. Carbon will also be absorbed until the saturation point is reached at about 3½ to 5 per cent carbon.

It is further essential that the iron be not only fused but, indeed, superheated, in order that it may remain fluid until drained from the furnace and cast into pigs or transported to steel furnaces.

311. Conversion of Gangue to Fusible Slag. The function of the slag formed in the blast furnace is primarily the elimination of all nonvolatile matter in the gangue of the ore and in the fuel which does not properly belong in pig iron. This can be accomplished only by giving to the slag such a composition that it will offer a greater attraction to the impurities than does the metal.

The slag-making materials consist of the gangue of the ore, the ash of the fuel, and the lime of the flux. The chemical nature of the slag and consequent metallurgical action is controlled by varying the relation of lime (added as a flux) to the other slag-making constituents in the furnace charge. The three slag-making materials upon fusion form a molten silicate of lime, together with magnesia and alumina. The alumina and earthy and alkaline bases naturally enter into the slag, since they exist as oxides and are not reduced in the furnace. In addition, the bulk of the silicon will enter the slag as silica (SiO_2), and most of the sulphur, by an entirely chemical action, enters the slag as sulphide of calcium, which, although an unoxidized body, does not unite with the molten iron, but appears to dissolve in the slag. (This is the only important exception to the fundamental metallurgical principle above stated.)

312. Separation of Iron and Slag. The separation of molten iron from molten slag follows as a necessary consequence of the operation of the principle that unoxidized bodies in a state of fusion will not unite with oxidized ones. Since the two substances are chemically mutually repellant, the fact that both are very fluid and of different specific gravities affords the only circumstance necessary to make their mechanical separation easy. The slag floats upon the molten iron in the hearth of the furnace and may be readily tapped off through the cinder notch above the level of the iron.

OPERATION OF THE BLAST FURNACE

313. Starting the Furnace. A new furnace must be first dried for several days by a wood fire built in the hearth. After drying, a scaffold is built just above the tuyeres and two or three courses of cord-wood placed vertically are laid thereon. The wood is followed by a blank charge of coke (mixed with enough lime to flux its ash) extending to a point about midway in the height of the furnace. Upon this bed of coke the charges of fuel, ore and flux are begun and the furnace completely filled. Kindling is placed beneath the scaffold, kerosene is introduced in the tuyeres, the top of the furnace is opened, a light blast started, and the kindling ignited.

The top is kept open until the wood smoke disappears, after which the gases are taken care of by the down-take. Charging continues as the stock line settles, the proportion of ore and flux to fuel being gradually increased until the normal burden is reached in a week or ten days.

From now on the charging is continuous, the stock line being kept at a practically constant elevation just below the down-take outlets.

314. Mechanical Control of Furnace and Accessories. The computed proportions of ore, flux, and fuel are weighed in the ore larries before being discharged into the loading skips. The upper hopper usually will hold only one skipload of material, but the lower hopper is not discharged until it contains several skiploads, constituting a properly proportioned furnace charge. Various devices are used for accomplishing an even distribution of the stock as it falls into the furnace, the intention being the prevention of segregation of the coarse and fine material.

The hot-blast stoves are controlled by a series of valves, one of which regulates the admission of gas, a second the admission of air from the blowing engines, a third the outlet of hot gases to the furnace, and a fourth the chimney draught while " on air." All of these valves except the air-inlet, which is a simple gate valve, are usually water-cooled mushroom valves.

The temperature of the furnace is mechanically controlled (aside from the effect secured by varying the burden of the furnace) by control of the temperature and pressure of the air blast, and this is accomplished by regulation of the hot-blast stoves and by regulation of the revolutions per minute of the blowing engines.

The slag must be tapped off within ten to fifteen hours after starting the blast and thereafter about every two hours, the interval becoming shorter as the level of the molten iron rises toward the level of the slag notch. The iron is tapped about twenty to thirty hours after starting the blast and thereafter at intervals of about four to five hours. Peep holes are provided in the furnace walls so that the proper time for tapping slag or iron may be observed.

The cinder notch is opened up by use of a pointed bar, and closed by holding in the hole a bar (having an enlarged end) until the cinder chills against it. The iron notch is opened by drilling through the clay which closes it, and finally driving in a pointed bar. It is closed either by cutting off the blast and driving in balls of clay by hand tools, or by a machine called the "gun" (Fig. 153), which by action of a piston drives balls of clay into the tap-hole without requiring complete cutting off of the blast pressure.

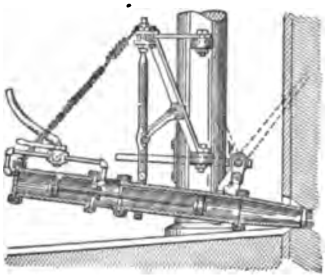


FIG. 153.
Gun for Plugging Tap Hole.

The subsequent handling of the products will be considered in a later chapter.

315. Metallurgical Control of Furnace. *Control of Deoxidizing Agencies.* The strength of the deoxidizing agencies may be regulated by controlling the hearth temperature, by varying the furnace burden, and by varying the slag composition.

The hotter the furnace temperature is, the more powerful will be the deoxidizing action of carbon upon iron, silicon, calcium, manganese, phosphorus, etc. Increasing the fuel ratio has naturally a direct effect upon furnace temperature, and an indirect effect in increasing the deoxidizing action. Increasing the lime-magnesia content of the slag has the effect of raising its melting-point and as a result, as we shall later see, the hearth temperature is again increased with consequent increase in the strength of deoxidizing agencies.

Control of Hearth Temperature. The hearth temperature may be raised in three ways: by increasing the proportion of fuel to ore and flux; by raising the blast temperature and pressure; and by making the slag more infusible. The first and second methods need no further explanation. Making the slag more infusible raises the hearth temperature because a very fusible slag becomes very fluid high up in the melting zone and rapidly traverses the hottest part of the furnace without opportunity to absorb much heat. A less fusible slag, on the other hand, will descend slowly through the hottest part of the furnace, gradually melting and becoming superheated, so that when it finally trickles down into the hearth it will convey a great amount of heat thereto.

Burdening the Furnace. The proportion of ore and flux to the fuel in the furnace charge is called the furnace "burden." Successful operation depends more upon the proper burdening than upon any other single factor in the furnace management. The method of determining the furnace burden is somewhat complex, and is dependent in its details upon the experience gained in the use of a given ore or ores. No attempt will here be made to explain the process in more than a general way.

The composition of the slag to be produced, or at least the ratio of acids to bases, must be first assumed, the assumption being based upon the experience of the manager in the use of given materials and upon the character of pig iron required. If, for instance, an iron suitable for basic steel-making is required, the silicon must be below 1.0 per cent and the sulphur below 0.04 per cent. If a low grade Bessemer pig is required, the silicon must not exceed about 1.5 per cent, the sulphur must not exceed 0.05 per cent, and the phosphorus must be below 0.1 per cent. A foundry pig requires 2 to 3 per cent silicon, less than 0.06 sulphur, and 0.5 to 1.0 per cent phosphorus. In general a basic steel pig requires a high temperature and a basic slag ($SiO_2+Al_2O_3$ below 45 per cent); Bessemer pig requires a high temperature and a neutral slag ($SiO_2+Al_2O_3=47$ to 48 per cent); and foundry pig requires a high temperature and an acid slag ($SiO_2+Al_2O_3$ above 50 per cent).

It is now essential that the complete analysis of ore, fuel, and flux be known. The " available base " of the flux is determined by deducting from the total percentage of bases in the flux the portion required to neutralize the acids in the flux. The quotient obtained by dividing 100 by the available base is termed the " efficiency of the flux."

The amount of flux required to neutralize the excess of acids over bases in the fuel ash may now be determined by multiplying the total acids by the ratio of acids to bases in the slag (the slag ratio), thus fixing the total bases required, subtracting therefrom the total bases in the fuel, and multiplying the remainder by the flux efficiency.

The flux required to neutralize the excess acids in the ore is similarly computed (taking account of the fact that a portion of the silica becomes reduced in the furnace and cannot therefore be included in the total acids). The flux required for each of the above offices is now expressed in tons of stone per ton of pig iron produced and the total, when a slight addition has been made to flux the sulphur, will express the total tonnage of limestone to be charged per ton of pig iron made.

The tonnage of ore required per ton of pig iron produced may be calculated directly from the percentage of iron in the ore; and, lastly, the amount of fuel required per ton of iron produced is determined. This last factor is fixed by two considerations: first, the amount of carbon required to form and melt the slag, and second, the amount of carbon required to reduce, carbonize, and melt the pig iron. These requirements are separately computed, the factors employed being largely determined by the experience of the furnace manager. In general the weight of carbon needed to satisfy the slag requirements will be in the neighborhood of one-fourth the total weight of slag produced per ton of iron, and the iron requirement (although variable because of variation in silicon content of the pig), will usually be in the neighborhood of 0.07 per cent of the weight of the pig. The quotient of the total carbon required by the percentage carbon in the fuel is the coke required per ton of pig produced.

To give an approximate idea of the relative amounts of ore, flux, and fuel in a charge, it may be added that for an average Bessemer pig having about 1.5 per cent silicon and made from ore containing about 55 per cent iron, the weight of fuel required will average in the neighborhood of one-half the weight of the ore, and the flux will average roughly one-fifth the weight of the ore.

Very commonly in American practice two distinct kinds of ore must be charged, one a soft earthy ore such as is mined on the Messabi range, the other a rock ore which must be used to prevent clogging of the furnace by the earthy ore. The problem of determining the furnace burden is not materially affected except that the two ores must be considered separately, and the proportion of each as well as the fuel and flux requirements of each are separately determined.

Varying the Slag Composition. It has been noted above that the hearth temperature, the sulphur content, and the silicon content of the pig iron are largely dependent upon the melting-point of the slag, and the melting-point of the slag is controlled by varying the ratio of bases to acids in the slag. We have seen that increasing the lime-magnesia content raises the melting-point of the slag with consequent increase in hearth temperature and strength of deoxidizing agencies. This has the effect of raising the silicon content and lowering the sulphur content of the iron. The removal of sulphur is especially facilitated by the presence of an excess of lime and magnesia. The melting-point of the slag is controlled in actual practice by varying the proportion of limestone charged.

316. Action within the Furnace. *Solids and Gases.* In consequence of the fact that all of the solid material used in the blast furnace is introduced at the top, while the fourth necessary material, the air, enters at the bottom, we may consider that we have in the furnace two moving currents; one a slow current of descending solids, the other a rapid current of ascending gases. The interactions of these two currents constitute the greater part of the changes which take place outside of the smelting zone.

The Fuel and Heat Development. The primary source of heat in the furnace is naturally the carbon of the fuel, and if all of the carbon were completely burned the total heat developed would simply be 14,550 B.T.U. per pound of carbon. Since the furnace gases are combustible, however, it is evident that not all of the carbon is completely burned, and since pig iron contains carbon, it is further evident that a part of the carbon is not burned at all.

The carbon that is used to reduce the oxides of iron, silicon, manganese, phosphorus, etc., is all completely burned to CO_2 with the development of 14,550 B.T.U. per pound. The balance of the carbon in the fuel, after that absorbed by the iron and a further quantity required to reduce the CO_2 of the flux to CO (because CO_2 cannot exist in the portion of the furnace where $CaCO_3$ breaks up into CaO and CO_2) has been deducted, is burned to CO with the development of only 4450 B.T.U. per pound.

In addition to the heat developed by the burning of carbon there is a secondary source of heat—the heat in the air blast which enters at a temperature of 425° to 650° C. The heat so introduced directly into the hearth may amount to as much as one-third of the heat developed in the hearth, and perhaps one-fifth of the total heat developed in the furnace.

Chemical Reactions. The exact nature and sequence of chemical reactions in the blast furnace is not easily determined and, in view of the divergence in opinions of various authorities, the discussion will here be only a general one.

Fig. 154, taken from Campbell's "Metallurgy of Iron and Steel," represents graphically the chemical phenomena of a blast furnace with probably a fair degree of fidelity. The conditions assumed are as follows:

Temperature at tuyeres, 1500° C.
Ore = 60 per cent Fe; no water.
Coke = 87 per cent C; 1888 pounds per ton of iron.
Stone = 100 per cent $CaCO_3$; 1010 pounds per ton of iron.
Pig iron = 4 per cent C; 1 per cent Si.
Volume composition of escaping gases = 1 part CO_2, $1\frac{1}{2}$ parts CO.
Temperature of escaping gases = 260° C.
Height of furnace = 90 feet.

An analysis of the diagram will establish the following sequence of chemical actions:

The ore as it enters the furnace encounters an atmosphere of gases made up of 16 per cent CO_2, 24 per cent CO, and 60 per cent N, at a temperature of 250° C. The Fe_2O_3 of the ore immediately begins to be reduced by CO, forming Fe_3O_4 with the evolution of CO_2 and attended by the freeing of a certain amount of carbon. (This carbon becomes deposited in the form of lamp-black upon the solid material of the charge and on the walls of the furnace.) At a temperature of about 500° C., reached when the material has sunk about $13\frac{1}{2}$ feet below the stock line, the newly formed Fe_3O_4 begins to be further reduced by CO to form FeO, attended by the further evolution of CO_2. This action is represented as completed at a temperature of about 580° C., at a depth of 19 feet.

The FeO begins to be reduced by CO to metallic iron at a temperature of 700° C., and practically none exists at temperatures above 800° C. The iron at this time assumes a spongy form. (It is probable that the diagram is in error, since it has been quite authentically shown that by far the greater part of the reduction of the ores to metallic iron is completed at a depth of not more than 12 feet. It is also probably in error in representing the solid carbon deposit as constant all the way down to the tuyeres, because owing to the presence of CO_2 liberated by the breaking down of the limestone, it is rapidly oxidized to CO, and probably only a small portion of it reaches the bosh.)

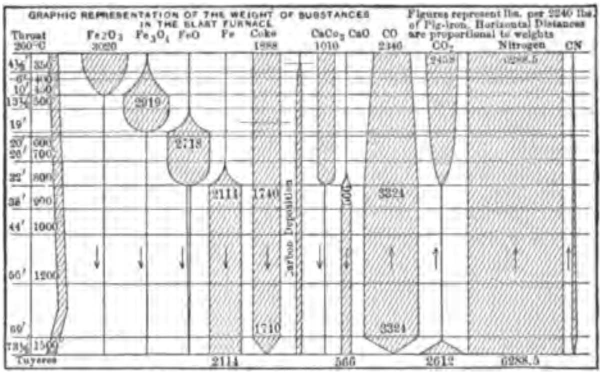


FIG. 154.—Graphical Representation of Chemical Action within Blast Furnace (Campbell.)

The decomposition of the limestone begins at a temperature of about 800° C. and is represented as completed immediately, though it is probable that some raw limestone exists at a considerably lower level. The CO_2 liberated is, as shown above, rapidly reduced by C to CO, while the lime descends to the zone of fusion to flux the acid portion of the charge.

The travel of the materials through the region between the point of completion of the decomposition of limestone and the upper limit of the smelting zone is characterized by no chemical action. During this transit the materials absorb much heat, however, and the temperature rises steadily as the tuyeres are approached.

The portion of the furnace constituting the lower part of the bosh is called the "smelting zone." It is characterized by chemical actions mainly impossible above this zone because of insufficiently high temperatures. The air of the blast is immediately broken up at the tuyere level into oxygen and nitrogen, and the latter, being practically inert, passes upward in substantially its original volume. (A small amount may combine with carbon and potassium or sodium to form cyanides.) The oxygen immediately burns the carbon of the coke to CO_2, which is in turn rapidly reduced to CO.

The smelting zone is from a chemical point of view primarily the zone of reduction of the metalloids—manganese, silicon, and phosphorus—through the agency of solid carbon, and the removal of sulphur through the joint agency of the lime of the flux and the carbon of the fuel.

Manganese is present as the dioxide, MnO_2; silicon as silica, SiO_2; phosphorus as phosphoric acid, P_2O_5; and sulphur as ferrous sulphide, FeS. The reduction of the oxides of manganese, silicon, and phosphorus by carbon is in each case attended by the evolution of CO. Perhaps two-thirds of the manganese will under ordinary conditions be reduced and therefore be found in the iron. Silica is not so readily reduced, the extent of the reducing action being largely dependent, as above noted, upon the hearth temperature and the basicity of the slag. In general the amount reduced and found as silicon in the pig will not exceed about one-fifth of the amount present in the charge. Phosphoric acid is readily reduced at the temperature of the smelting zone and practically all of the phosphorus in the charge will therefore be found in the pig iron.

The behavior of sulphur in the smelting zone is not analogous to that of the metalloids above considered. Whatever the original form of the sulphur in the charge it will probably reach the smelting zone in the form of ferrous sulphide, which is soluble in iron. Sulphur is an acid radical, however, and therefore readily combines with the bases of the slag, particularly lime, and is thereby removed in the slag in the form of calcic sulphide, CaS. Iron is thereby restored to the metal, and the oxygen liberated in the presence of carbon reacts to form CO again.

The reduction of metalloids in the smelting zone is not represented in Fig. 154 because the scale of the diagram is such that the small quantities of matter involved could only be represented by a single line.

317. Handling the Products. *The Iron.* The iron when tapped from the furnace is handled in one of two general ways—by casting into pigs, or still molten in ladles.

Formerly all the iron was cast in sand pig-beds, which consist of a series of parallel depressions molded in a bed of silica sand on the floor of the cast-house. Fig. 155 shows the layout of such a pig-bed. The individual depressions are connected to cross runners which in turn connect with the main runner leading from the tap hole.

Sand casting is now seldom used except in small works, principally because of the fact that the silica sand which adheres to the pigs renders the iron unfit for steel manufacture.

A modification of the sand pig-bed, the " chill pig-bed," is now sometimes used. It is simply a pig-bed made of cast iron, molded in shape very similar to that of the sand pig-bed, but not requiring any preparation beyond sprinkling with a clay wash to prevent the pig iron from sticking to the molds or melting them.

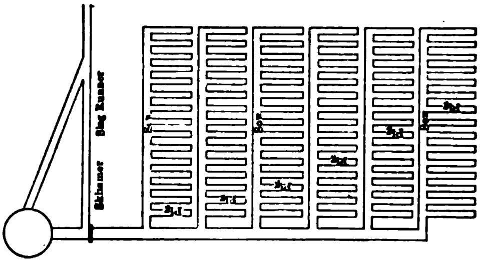


Fig. 155.—Sand Casting Pig-bed.

The iron pigs are broken from the cross runners by hand sledges and bars or by a mechanical pig breaker, and the cross runners are similarly broken up into convenient lengths.

A large proportion of the iron now molded into pigs is cast in pig-molding machines, one type of which is illustrated by Fig. 156. The machine consists essentially of a continuous series of pressed steel molds carried on an endless chain. The iron runner of the furnace delivers the molten iron into a ladle which is discharged into a spout whence the metal is poured into the molds as they slowly travel past. The iron quickly chills and is discharged into a car when the mold passes over a sheave at the end of the run. On the return the molds are immersed or sprayed with limewater to prevent the pigs adhering. The cooling of the pigs is usually facilitated by depressing the chains and running them through a tank of water.

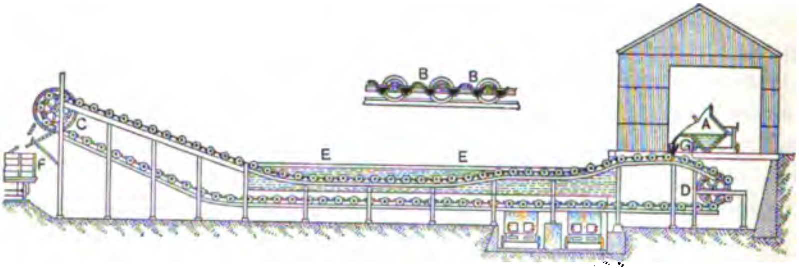


Fig. 156.—Pig-moulding Machine.

The blast furnace is now so often operated in direct conjunction with a steel plant that the iron is very commonly not cast into pigs at all, but is run directly into ladles which transport it to the steel furnaces. Fig. 157 shows one common type of ladle. The ladle is built of steel, mounted on trunnions on a car-truck, and lined with firebrick. Its capacity is usually 20 tons or more.

Slag Handling. The slag which accumulates above the level of the cinder notch is tapped off at intervals of about two hours, while the iron notch is closed. When the iron notch is opened iron free from slag flows at first, but later on in the cast a quantity of slag accompanies the iron, floating on top just as it does in the hearth. This slag is easily separated from the iron by a "skimmer" placed in the main iron runner. The skimmer (Fig. 158) now usually consists of a permanent cast-iron trough, having a depression followed by a dam over which the iron must flow. The skimmer is suspended (in slots in the side of the trough) over the depression at such a height that it rests on top of the stream of iron and effectually prevents the slag from being carried over the dam. An opening in the side of the trough allows the slag to overflow into a runner, whereby it is carried to the main slag runner which leads from the cinder notch to the point where the slag is discharged into ladles and carried to the slag dump.

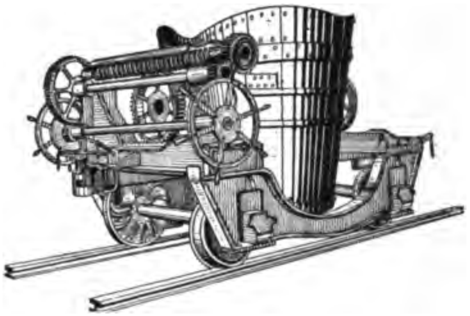
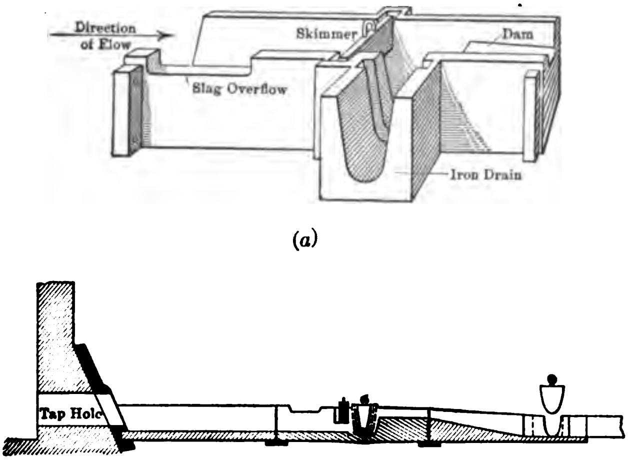


FIG. 157.—Hot-metal Ladle.



(a)

(b)

FIG. 158.—Cast-iron Slag Skimmer.

THE ELECTRIC REDUCTION OF IRON ORES

318. General Considerations. The electric furnace has been used in the metallurgical industries for a considerable period, but it is only within the last few years that the difficulties in the way of practicable operations have been removed to such a degree that pig iron has been successfully produced on a commercial scale.

The conditions under which the electric reduction of ores can be successfully carried out are definite, and restricted for the present at least to only a few districts. The following considerations will make the matter clear:

In the blast furnace fuel must be supplied to serve two purposes: (1) the introduction of carbon, the oxidation of which supplies the necessary heat; and (2), the introduction of carbon to act as a reducing agent. In the electric furnace, on the other hand, the requisite heat is supplied by electrical means and the only carbon required is that needed for strictly reducing purposes. It has been shown that the electric furnace needs from one-third to two-ninths the amount of carbon required by the blast furnace. This therefore means a great saving in the amount of fuel required.

On the other hand, the cost of heat produced by electrical means will greatly exceed the cost of heat produced by the combustion of fuel except under unusual conditions, which obtain only in ore districts where the price of fuel is very high and electric power very low. It is only in such districts, therefore, that the commercial extraction of iron by electric means has been or for the present can be successful.

319. The Electric Furnace. Many types of electric furnaces have been used in the metallurgical industries, the principal classes of which may be classed as follows:

a. Furnaces using electrodes with an open arc, the heating being done by radiation, called " arc furnaces."

b. Furnaces using electrodes that project into the charge or the bath, called " resistance furnaces," and

c. Furnaces without electrodes where the bath forms the secondary of a transformer, called " induction furnaces."

Only furnaces of the second or resistance type have been employed in the smelting of ores. Fig. 159 shows the general arrangement of the furnace which has been in operation at Domnarfvet, Sweden, for several years, and Figs. 160 and 161 show a modification of the Domnarfvet furnace built at Trollhätten, Sweden, in 1910. This latter furnace is practically a duplicate of furnaces independently developed in the United

States at Heroult, California, at about the same time. In its essentials the furnace may be described as follows:

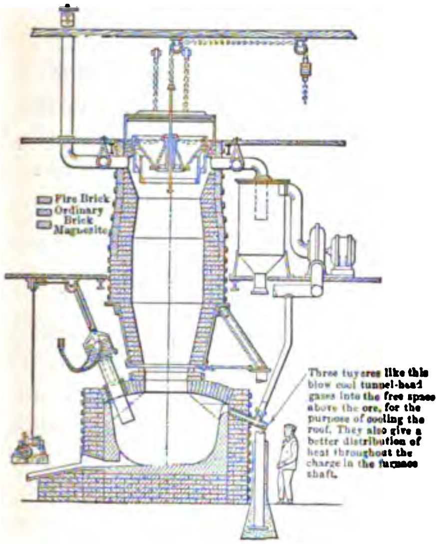


Fig. 159.—Electric Ore Smelting Furnace. Domnarfvet, Sweden.

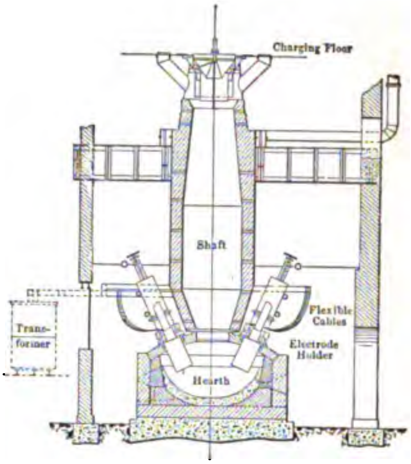


Fig. 160.—Electric Ore Smelting Furnace. Trollhätten, Sweden.

The upper portion of the furnace presents an appearance very similar to that of an ordinary blast furnace except that it is much smaller. This portion, the shaft, is supported on columns over a large crucible which is lined with magnesite and provided with the usual tap-holes for slag and iron. The shaft is provided with the usual charging arrangement of hopper and bell, as well as gas outlets, bleeder, downtake and dust-catcher.

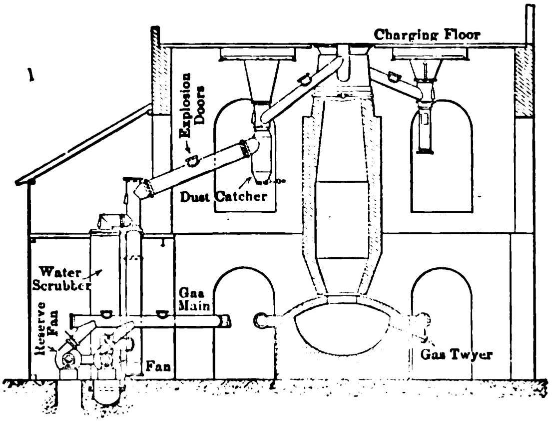


Fig. 161.—Trollhätten Furnace, Showing Gas-circulating System.

The current is introduced through six electrodes (24 inches in diameter by 6 feet long) which are carried by adjustable mountings so that the depth to which they project into the charge may be kept constant as they become burned away. The electrodes are built of carbon and are fitted with a screw and socket so that they can be screwed together, end to end. When an electrode has been lowered as far as it will go, a new electrode is screwed on to its top and thus no part is wasted.

Three-phase current, capable of adjustment between 50 and 90 volts, is used. The material of the charge conducts the current, and its electrical resistance develops the necessary heat for smelting. The actual reduction of the ore is accomplished as in the blast furnace through the agency of the carbon supplied by the fuel, the amount required being only one-third that required in the blast furnace. Charcoal has thus far always been used instead of coke in the electric furnace.

The reduction of the oxides through the agency of carbon evolves CO and CO_2 gases which pass upward, giving up their heat to the charge in the shaft and performing some reduction in that region through the agency of the CO. The weight of gases evolved in the electric furnace is hardly one-tenth the weight of gases derived in smelting the same quantity of iron in the blast furnace, because no air is driven into the hearth. In consequence of this fact the gases have little heat-carrying capacity, and the heat generated in the hearth is not carried to the upper part of the furnace in anything like the degree attained in the blast furnace. This results in failure to heat the charge to the red heat required for reduction by CO in that region. The solution of this problem has thus far been met by repeated circulation of the gases. After passing the dust-catcher the gases are led through a condenser, where they are cooled sufficiently to remove most of their moisture, after which from one-half to two-thirds of the gas is forced by a blower back to the hearth through tuyeres arranged so that the gas impinges against the crucible arch, thereby cooling it.

This arrangement results in causing three or four times the natural amount of gas to pass up the shaft, carrying a proportionally greater amount of heat into the preheating zone, and thus facilitates the reduction of ore by CO.

No electric furnaces have been built in sizes to compare at all with the blast furnaces in daily output. The largest furnaces thus far built have a capacity of only 15 to 18 tons of pig iron per day. The industry is just in its infancy, but shows great promise for the future.

320. Quality of the Product. The pig iron produced in the electric furnace far excels in quality the usual output of the coke-fired blast furnace, and equals or excels the famous Swedish charcoal pig iron. This may be attributed largely to the fact that it does not contain any of the oxides which are frequently present in pig iron, owing to oxidation by the blast in passing the tuyeres. The absence of nitrogen is also probably a large factor. Still another metallurgical advantage lies in the fact that the temperatures are very high and easily controlled, and the hearth lining is basic, so that a large proportion of lime may be charged, making possible a very basic slag which facilitates the removal of sulphur and even some phosphorus. These considerations have great weight when it comes to making high-grade steel from pig iron.

THE USES OF PIG IRON

321. Classification of Pig Irons. Pig irons are classified according to (*a*) method of manufacture, (*b*) the purpose for which they are intended, and (*c*) composition.

a. Method of manufacture.

1. Coke pig: smelted with coke and hot blast.
2. Charcoal pig: smelted with charcoal, with either hot or cold blast.
3. Anthracite pig: smelted with anthracite coal and coke, with hot blast.

b. Purpose for which intended.

1. Bessemer pig: for Bessemer or acid open-hearth process.
2. Basic pig: for basic open-hearth process.
3. Malleable pig: for malleable cast iron.
4. Foundry pig: for gray cast iron.
5. Forge pig: an inferior foundry pig used for manufacture of wrought iron.

c. Chemical composition.

1. Silicon pig: high in silicon.
2. Low phosphorus pig.
3. Special low phosphorus pig.
4. Special cast irons (spiegeleisen, ferro-manganese, ferrochrome, etc.).

Any of the above irons may be called "sand-cast pig," "chill-cast pig," or "machine-cast pig" according to the method of molding.

Of the above classifications the second is by far the most commonly used.

The composition of the different grades is usually specified within the following limits:

	Silicon.	Sulphur.	Phosphorus.
Bessemer pig	1–2.00%	not over 0.05%	not over 0.10%
Basic pig	under 1.00	under 0.05	not specified
Malleable pig	0.75–2.00	not over 0.05	not over 0.20
Foundry pig	1.50–3.00	not over 0.05	0.50–1.00
Forge pig	under 1.50	under 0.10	under 1.00

322. The Uses of Pig Iron. Pig iron as such has no structural uses, but a considerable amount is used after remelting in the shape of cast iron. By far the greater part of all of the pig iron made is converted into steel either by the "Bessemer process" or the "open-hearth process" or into wrought iron by the "puddling process." All conversion processes have for their primary object the elimination of the greater part of the non-ferrous elements present in the pig. Any of these processes will reduce the carbon content to any desired point, while the silicon and manganese are necessarily eliminated during the carbon reduction. Phosphorus and sulphur are also reduced by the puddling process and by a special form of open-hearth process called the " basic open-hearth process." The difference between various steels and wrought iron are not so much a matter of chemical composition as they are a matter of physical characteristics which are dependent largely upon the conditions of conversion. The details of the different conversion processes will be taken up later.

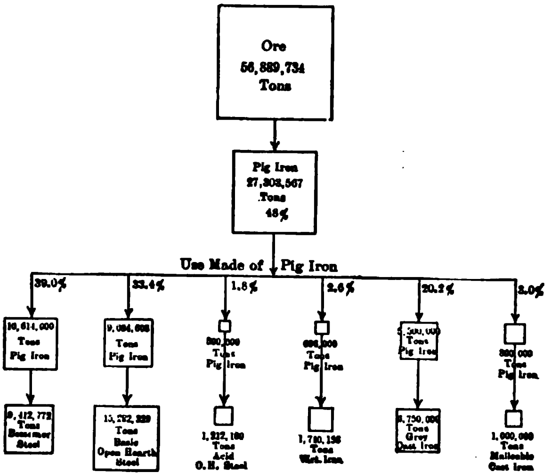


FIG. 162.—Uses of Pig Iron. 1910.

By reference to Fig. 162 (based upon the statistics for 1910) it will be seen that of the total production of pig iron in the United States about 39 per cent is used in the production of Bessemer steel, 35.2 per cent for open-hearth steel, 23.2 per cent remelted into cast iron, and 2.6 per cent converted into wrought iron. (Proportionate areas on this diagram represent proportionate tonnages.)

These figures do not represent the relative amounts of cast iron, wrought iron, and steel produced, because, as we shall later see, the ratio of pig iron used to finished material produced is not fixed, but varies for the different processes, being high for Bessemer steel and cast iron, and low for open-hearth steel and wrought iron where large amounts of scrap steel and iron are used in the furnace charges.

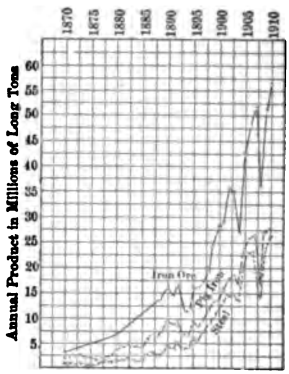


FIG. 163.
Production of Pig Iron.

323. Production of Pig Iron. The production of pig iron in the United States in its relation to ore production and steel production is shown graphically in Fig. 162 for the year of 1910, and the production for the last forty years is shown by the diagram of Fig. 163, taken from "Mineral Resources of the United States," 1913.

The production of ore and pig iron during the period from 1910 to 1913 is reported as follows: (Long tons.)

	1910.	1911.	1912.	1913.
Iron Ore	57,014,906	43,876,552	55,150,147	61,980,437
Pig Iron	27,303,567	23,649,547	29,726,937	30,966,152

CHAPTER XII

CAST IRON

INTRODUCTORY. PIG-IRON PRODUCTS CLASSIFIED.

324. Pig-iron Products. The principal commercial forms of iron and steel made from pig iron have been indicated above in Art. 322 and in Fig. 162. It will now be necessary, before considering the various individual forms of iron, to make a systematic classification of pig-iron products for purposes of future reference. The scheme presented below is, with minor modifications, that proposed by Howe for the purpose of clarifying the nomenclature of iron and steel.

CLASSIFICATION OF IRON

I. CARBON CLASS. (Properties chiefly dependent on carbon content.)

A. Weld Metal. (Aggregated from pasty mass without later fusion.)

1. Wrought iron. ($C = 0.20\%$ or less.)
2. Blister steel. ($C = 0.20–2.20\%$.)

B. Cast of Ingot Metal. (Cast as distinguished from aggregated.)

1. Steel. (Malleable when cast.)

a. Low-carbon steel.	($C = 0.20\%$ or less)	1. Bessemer steel.
b. Medium steel.	($C = 0.20–0.30\%$)	2. Open-hearth steel.
c. High-carbon steel.	($C = 0.30–2.20\%$)	3. Crucible steel.
		4. Electric steel.

2. Cast Iron. (Not malleable, $C = 2.20\%$ or more.)

a. Gray cast iron. (Carbon in graphitic state.)
b. White cast iron. (Carbon in combined state.)
c. Mottled cast iron. (Carbon partly in graphitic state.)

3. Malleable Cast Iron. (Cast and then rendered malleable.)

II. Alloy Class. (Properties chiefly dependent on content of elements other than carbon.)

A. Special or Alloy Steels. (Useful immediately for special purposes.)

1. Nickel steel.
2. Manganese steels.
3. Chrome steels.
4. Tungsten steels. (High-speed steels.)
5. Molybdenum steels.
6. Vanadium steels.
7. Titanium steels.
8. Silicon steels.

B. Ferro Alloys. (Used only to introduce certain elements into steels.)

1. Ferro nickel.
2. Ferro manganese.
2a. Spiegeleisen.
3. Ferro chrome.
4. Ferro tungsten.
5. Ferro molybdenum.
6. Ferro vanadium.
7. Ferro titanium.
8. Ferro silicon.

325. Cast Iron as a Material of Engineering Construction. Cast iron differs markedly from the other general classes of iron products—wrought iron and steel—both in chemical constitution and in physical characteristics. It possesses a very complex constitution which is extremely subject to variation with slight variations in details of manufacturing processes; it is comparatively coarsely crystalline in structure, possesses considerable hardness, but lacks toughness, melts readily and passes suddenly into a very fluid state, in which condition it will take a quite perfect impression of a mold, but it is nonductile at all temperatures and cannot be deformed (as in forging operations) without being broken.

Cast iron is not used structurally to nearly the extent to which both wrought iron and steel are so used. It is used to a certain extent, however, for columns and posts in buildings, also for column bases, bearing plates, and innumerable minor structural parts. In machine construction it finds its widest field of application, for no other metallic material which can be cast in complex forms can be produced with such ease and at so low a cost. In this field its principal competitors are malleable cast iron, cast steel, and cast brasses, bronzes, etc. Each of these materials possesses valuable properties not possessed by cast iron, such as greater strength, toughness, or non-corrodibility. When the conditions of service are ones that cast iron can meet, however, it has no competitors.

THE REMELTING OF PIG IRON

326. Iron Melting in General. A certain small amount of iron castings are made by running the metal into molds just as it comes from the blast furnace. Ingot molds, for instance, are made in this way at steel works. The variability of the blast-furnace product, however, and the difficulty in judging the character and correcting the composition of the molten pig iron, limits the making of " direct castings " to a rather restricted class of products. The bulk of all the iron used as " cast iron " is remelted either in the " cupola furnace " or the " air furnace " before being cast in molds.

The process of remelting the iron in the cupola resembles the process of melting ore in the blast furnace, but the reducing action of the blast furnace is not here present. The only office of the air blast used is the oxidation of the fuel of the charge. Remelting in the air furnace bears no resemblance to cupola melting, since the charge is melted in a hearth out of contact with the fuel. The heat is supplied by radiation and reflection from the flame of a soft coal fire maintained in a firebox adjoining the hearth.

The Materials Used

327. Foundry Pig Iron. Foundry pig irons were formerly graded, largely upon the basis of appearance of the fracture, as No. 1 Foundry, No. 2 Foundry, No. 3 Foundry, Foundry Forge, etc., the lower numbers representing pigs high in total carbon and silicon, and low in sulphur, phosphorus, and manganese, while the higher numbers and the forge grades are less choice irons, running higher in sulphur, phosphorus, and manganese, and low in carbon and silicon.

At the present time the iron used for foundry purposes is practically all bought by analysis, the content of silicon and sulphur being specified, and sometimes also the total carbon, manganese, and phosphorus.

In addition to the irons properly classed as foundry pig irons, Bessemer pig, ferro-silicon, and a few other special pig irons are used at times to bring the composition of the cast iron within the required limits.

328. Scrap Iron. The term " scrap iron " is used to designate that considerable portion of the iron charged into the furnace which has been remelted one or more times. It consists mainly of castings discarded after having been in service, but includes also defective castings, gates, sprues, etc., which have never left the foundry.

Some classes of castings such as water pipes, for instance, are made without any scrap. For others, the percentage sometimes runs as high as 30 or 40 per cent, the average amount used for all purposes being 20 to 25 per cent of the iron.

Scrap being less expensive than new pig iron, it is of course desirable that as much be used as is possible without rendering the cast iron unfit for the purpose for which it is intended. Scrap iron is necessarily extremely variable in composition and, owing to the practical impossibility of obtaining a representative sample for analysis, it is impracticable to attempt to grade it according to chemical composition. It is possible, however, to grade it with a fair degree of accuracy simply by inspection. The character of the fracture is, to an experienced observer, a much better indication of composition than it is in the case of pig iron, where the conditions of cooling and consequent opportunity for crystalline growth are much more variable.

329. The Flux. The office of a flux in the melting of iron is precisely the same as in the smelting of ores, i.e., to absorb and carry off in a slag the non-metallic residue of the iron and the ash of the fuel, and to assist in the removal of sulphur. Since the impurities in the charge of the melting furnace constitute only a very small proportion when compared with the amount present in the charge of the blast furnace, the percentage of flux required is correspondingly small. The requirements vary greatly, but in general will average in the neighborhood of from ½ to 1½ per cent of the weight of the iron.

The flux used is calcium carbonate, usually in the form of limestone, but oyster shells, marble chippings, dolomite, etc., are sometimes used, and a portion of fluorspar (CaF_2) is often added to obtain a more liquid slag.

330. The Fuel. The office of the fuel in iron melting is simply as a source of heat. The cupola is capable of developing a higher heat sufficiency than the air furnace because the fuel is in direct contact with the metal.

Coke is most commonly used as fuel in the cupola, although a mixture of coke and anthracite coal is sometimes used. The air furnace requires the use of a long-flaming bituminous coal. (In some cases gas is used.)

The fuel requirements depend upon the character of the castings being made, small and thin castings requiring a hotter metal than large castings. The cupola requires about 25 per cent of the weight of metal in fuel for hot iron, and 8 to 10 per cent fuel for the largest castings. The fuel requirements of the air furnace are about double those of the cupola.

THE FURNACE

231. The Cupola Furnace and its Equipment. The cupola in its essential arrangement is really a very small blast furnace, operated under a blast pressure hardly more than one-twenty-fifth that employed in the blast furnace, and intended only to melt the charge without any attempt being made to attain reducing conditions.

The type of cupola shown in Fig. 164 is representative of a great proportion of the cupolas used in good-sized foundries and in steel works. It consists of a vertical cylindrical shell of wrought iron or steel, lined with firebrick set in fireclay grout. The structure is supported on four columns about four feet from the floor. The size of the cupola is quite variable, ranging from about 22 inches inside diameter to about 100 inches, according to the amount of iron required. (55 to 60 inches has generally been found to be the most satisfactory size). The height is dependent upon the diameter, the usual practice being to locate the charging door at a height above the bottom plate equal to from 3½ to 4 times the internal diameter. The height of the stack above the charging door is governed by considerations of draft, and is therefore variable.

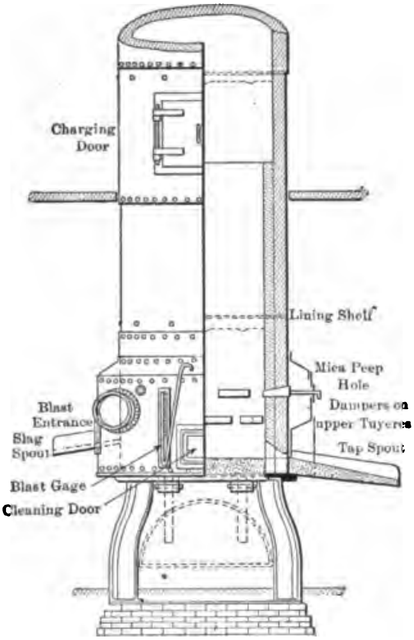


Fig. 164 —Foundry Cupola.

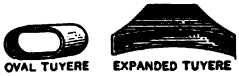


Fig. 165.—Cupola Tuyeres.

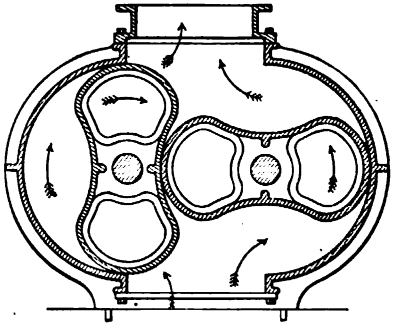


Fig. 166.—Two-impeller Blower.

The air blast enters the crucible through tuyeres leading from the "wind belt" or "air chamber" which surrounds the lower portion of the furnace. The tuyeres themselves are not elaborately constructed, but are usually simply iron castings set in the brickwork of the lining. The combined area of all the tuyeres amounts to from 15 to 25 per cent of the cross-sectional area of the cupola. (The larger figure applies when coke is burned and hot iron required, the smaller when coal is used and a less hot iron desired.) Fig. 165 shows two of the most commonly used forms of tuyeres. The tuyeres are usually arranged in two horizontal rings some 12 or 15 inches apart vertically, the area of the upper tuyeres being only a small fraction of that of the lower ones as a rule.

The slag hole is situated just below the tuyeres at a height of from 2 to 10 inches above the bottom plate, the height being governed by the amount of metal required per heat, and the provision or non-provision of a "fore-hearth," or "receiver" into which the metal flows from the hearth. (In American practice the English "fore-hearth" is not used, and the tuyeres are often just above the bottom except in the case of cupolas melting metal in steel works. In the latter case the amount of metal required is so great that extra hearth room is called for, necessitating the location of the tuyeres sometimes several feet above the bottom.)

The bottom of the furnace is what is called a "drop-bottom." That is, the bottom consists of two or more flap-hinged castings which are normally held in position by a prop beneath. At the conclusion of a "heat" or "cast" the prop is knocked out, allowing all the material remaining in the furnace to be "dumped."

The "tap-hole" or "spout" is located just at the level of the bed of sand which covers the bottom doors.

The air blast is derived by use of a positive-acting blower, usually of the two-impeller type shown in section by Fig. 166. This blower is very simple and free from mechanical weakness, and is capable of delivering large quantities of air under low pressures.

Attempts have been made to increase the efficiency of the cupola by heating the blast and by refrigeration of the air. All such attempts have ended in failure, however.

332. The Reverberatory or Air Furnace. The reverberatory or air furnace is so called because of the manner in which the furnace operates. The term " air furnace " is appropriate, since it distinguishes this type from the cupola, which, instead of natural draught, uses forced draught or blast pressure, and the term " reverberatory " applies, since the furnace employs the principle of utilization of heat (from flames sweeping through the melting chamber) derived by reflection from the roof upon the bath of the metal.

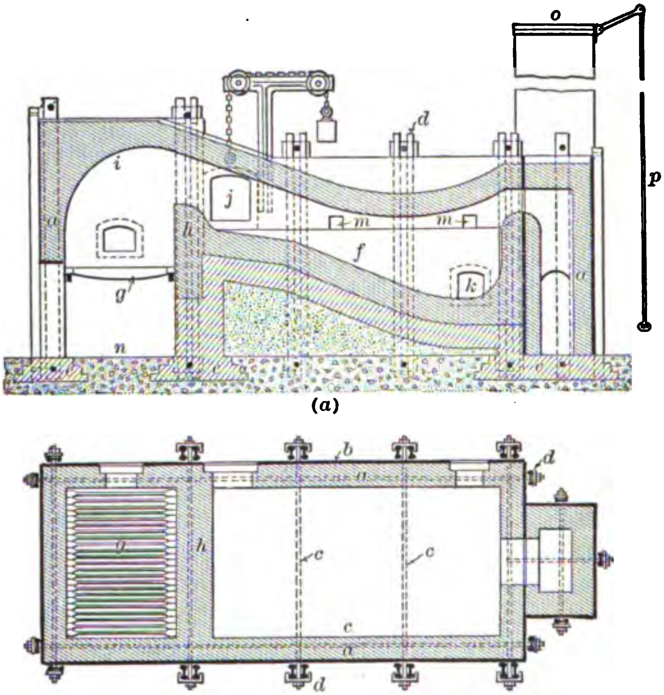
The design of air furnaces shows many variations, but for present purposes a description of one typical form will suffice. Fig. 167 shows such a furnace. The main portion of the furnace, the hearth (*f*), is flanked on one end by a firebox (*g*), and on the other by a flue leading to a stack (*o*). The walls of the furnace (*a*) are of very heavy brick masonry, incased in iron plates (*b*), and reinforced both ways by tie rods (*c*) between buckstays (*d*).

The hearth bottom is a mixture of sand and fireclay supported by brickwork built to slope downward from the "fire bridge" (*h*) to the flue bridge. The "crown" of the furnace is similarly inclined downward toward the stack in order to deflect the heat of the flames downward on the iron in the hearth.

The firebox is provided with iron grate bars, and fuel is introduced through a firedoor in one side wall of the firebox. Pig iron and scrap are charged in through the charging door (*j*), and holes (*m*) are provided to facilitate the skimming of the bath of metal. The spout is not shown in the figure, but is so placed as to drain the metal from the lowest part of the hearth.

Furnaces in which large amounts of iron, or bulky scrap iron, are melted often have removable sections in the crown through which the charge is lowered by cranes.

333. Relative use of Cupola and Air Furnace. The cupola is used for most foundry purposes in the production of gray iron castings and for melting iron for steel furnaces. The use of the air furnace is principally confined to the production of white cast iron for malleable cast iron, but it is also used to produce irons of special purity or particular composition for special purposes.



(a)

(b)

Fig. 167.—Air-furnace.

Operation of Cupola

334. Starting the Furnace. The usual method of starting consists in laying a bed of shavings and kindling-wood on the bottom, followed by heavier wood and then fine coke, and lastly a charge of the regular fuel is placed.

The tuyere doors are now opened, the shavings lighted at the front, and the fire allowed to burn up until all the fuel is well lighted. Then the tuyere doors are mostly closed and charging is begun.

A new method of lighting up is sometimes adopted, an oil torch being employed without the use of wood kindling. Openings or flues through the coke are made directly upon the sand bed by the use of thin boards, and the fuel is ignited by the torch flame entering at the front.

335. Charging. The bed of fuel having been properly prepared and leveled off, the charge of broken pig and scrap is carefully placed, an effort being made to fill up the interstices as far as possible and keep the charge level. The next charge of fuel is now placed on the iron, and alternate charges of iron and fuel continue until the height of the charging door is reached. When a flux is required, the proper proportion (usually ½ to 1½ per cent of the iron) is charged on top of each bed of iron, except at the start and at the end of the heat, when it may be omitted.

The charging of the furnace is often done two or three hours before the blast is started but, even if the blast is put on immediately after charging the iron, iron should begin to melt and appear at the tap-hole within fifteen or twenty minutes after starting the blast. If it does not, it indicates that the bed of coals has not been properly prepared.

336. Action within the Furnace.* When the furnace is properly operated it shows the following distinct zones of action, beginning at the bottom and proceeding upwards: (1) The crucible zone or hearth, (2) the tuyere zone, (3) the melting zone, and (4) the stack. These four zones are indicated in Fig. 168.

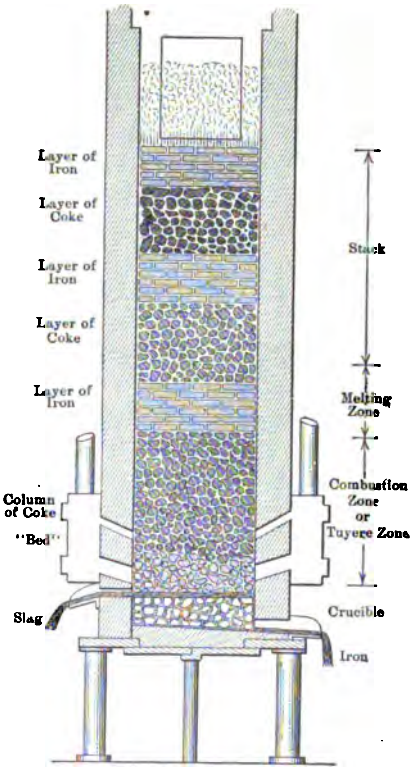


FIG. 168.—Zones in Cupola. (Stoughton.)

(1) The crucible zone extends from the bottom up to the level of the tuyeres. It serves the tole purpose of collecting and holding the molten metal and slag until sapped out. If the metal is allowed to run out of the spout continuously, this zone will be very short, the tuyeres being very close to the bottom. If the tuyeres are located high in the hearth a bath of considerable depth may be allowed to accumulate, but because of the cooling action of the blast from the tuyeres, it will not be as hot iron as that obtained

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* Bradley Stoughton, "The Metallurgy of Iron and Steel."

by collecting the metal in a ladle outside of the furnace. If slag is formed and allowed to collect on the bath of metal it will help to protect the latter from the effect of the blast.

(2) The tuyere zone is the zone of combustion. The blast here comes in contact with the red-hot coke and rapidly oxidizes it. A column of coke always extends from the melting zone to the bottom of the crucible, and combustion occurs from the level of the molten metal to a point above the tuyeres, the height of which is dependent upon the pressure of the blast. The blast pressure should not be sufficient to make the top of this zone more than 15 to 24 inches above the uppermost tuyeres. This pressure varies from about 1 pound per square inch for the largest cupolas, to about ½ pound per square inch for the smallest ones.

(3) The melting zone is situated directly above the tuyere zone. During the melting the iron is supported on a column of coke, extending to the bottom of the cupola, which is the only solid material below the melting zone. The iron as it melts trickles down to the bottom over the column of coke. Each layer of iron requires about 5 to 10 minutes to melt, and the column of coke is constantly sinking, so that the last of the iron melts several inches lower than the first. If the charges of iron and coke and the pressure of the blast are properly proportioned, each charge of iron will enter the top of the melting zone just before the last charge is completely melted at the bottom.

(4) The stack extends above the melting zone to the level of the charging door. Its function is to contain material that will absorb heat to bring it into good condition for action in the melting zone, and to keep the heat in the melting zone as much as possible.

The amount of air required for satisfactory operation is largely in excess of the amount theoretically required to burn the coke, on account of imperfect combustion and leakage. Thus, instead of using about 60 cubic feet of air per pound of coke burned, 100 cubic feet or more are actually supplied.

337. Chemical Changes. The chemical changes which take place in the cupola are for the most part incidental rather than intentional. The iron absorbs sulphur from the fuel in trickling down into the hearth to an amount varying from 0.02 to 0.035 per cent of the weight of the iron. On account of the excess of fuel burned before tapping, the sulphur is high at the beginning of the run, and, on account of the loss of metal through oxidation, the sulphur is high again at the end of the run. Limestone is decomposed, as in the blast furnace, and fluxes the dirt in the charge and the ash of the fuel. The slag formed absorbs a part of the sulphur, just as it does in the blast furnace, and also carries off whatever oxides (such as silica or iron oxide) may be formed.

The air of the blast oxidizes a small proportion of the iron, and similarly oxidizes an amount of silicon amounting to from 0.25 to 0.40 per cent of the iron. These latter changes of course mean a loss of metal.

The cupola gases consist mainly of the nitrogen of the air together with CO_2 and some CO. The presence of the latter indicates a failure to attain complete combustion of the fuel. All efforts to utilize this gas have resulted in failure, mainly, perhaps, because of the discontinuous operation of the cupola.

338. Duration of the Cupola Run. A foundry cupola is never run continuously, but is started anew for each casting and is " dumped " at the conclusion of the run. As a general rule the duration of the run does not exceed three or four hours, and it cannot exceed this period if no provision is made for draining off the slag. Some large cupolas operated in connection with steel plants are run continuously for six days in a week, at the end of which time, if not before, stopping is generally required to effect extensive repairs.

339. Tapping Out and Stopping In. The tap-hole is usually left open until the iron begins to run after the blast is started, at which time it is closed if an accumulation of metal is desired. Often the first iron is used only to warm the ladles which are subsequently to be employed in pouring the castings.

The " stopping in " is accomplished by the use of the " bod " and " bod-stick." The bod is a plug made of fireclay, sand, or molding sand, molded in the shape of a cone which adheres to the enlarged end of the " bod-stick," the latter being simply an iron bar with an upset end. The bod is thrust in quickly to stop the flow of metal and bakes hard enough to withstand the pressure. A soft bod of molding clay and sawdust is used when the cupola is tapped and stopped very frequently.

Tapping consists simply in piercing the bod by use of a round iron bar provided with a pointed end. It is an operation requiring great care, since the danger of causing molten iron to spill and burn those near at hand is ever present.

Operation of Air Furnace

340. The Charge. The small scrap, gates, etc., are first placed in the furnace hearth, followed by the flux and the pig iron or the large scrap, the latter being carefully stacked up to utilize all the space. The furnace is either still hot from the last melt, or it is heated for some hours before charging, so that melting begins soon after the charge is placed.

341. Control of Melting. The temperature of the furnace is controlled by the regulation of the draft by means of a damper in the stack or stack flue, and one in the firebox. The bituminous coal burns with a long flame which sweeps through the melting chamber, the conditions being strongly oxidizing rather than reducing. A slag soon forms and covers the metal as it accumulates, so protecting it in a measure from oxidation. The slag is not drained off, but must be skimmed from time to time. The furnace man also rabbles the charge, gradually pushing the pig down into the bath.

The time required for melting is much greater than in the case of the cupola, the actual time being dependent upon the capacity of the furnace. A 10-ton furnace will melt down a charge in three or four hours, while a 30-ton furnace will require eight or nine hours. The fuel requirement is about one-fourth the weight of the charge or about 35 per cent of the iron produced. The metal is tapped as rapidly as possible and, since the hottest metal is at the top of the bath, a series of tap-holes at different levels are sometimes used successively. The loss of metal due to oxidation amounts to from 2 to 5 per cent of the charge.

342. Advantages and Disadvantages. The product of the air furnace is purer than cupola iron, since the metal does not come in contact with the fuel. This means less absorption of sulphur and less absorption of carbon, resulting in general in a higher grade and stronger iron. The process being much slower than the cupola process, it is under better control and any desired composition can be more closely approached.

The cupola, on the other hand, is a cheaper installation, requires less skillful management and is therefore cheaper to operate, the heat is more uniform so that all the metal of a melt has more nearly the desired temperature, very hot iron is more easily obtained, the furnace can be started and stopped more readily, the fuel efficiency is greater, and there is less loss of metal through oxidation and consequent removal in the slag.

IRON FOUNDING

343. Iron Founding in General. The art of founding consists in pouring molten metal into a mold of any desired special form, which the metal assumes and retains when cold.

The most important part of iron founding is making the molds, a process which demands a very high order of mechanical skill and no small amount of manual labor.

No portion of the technology of iron is of more importance to the engineer and machine designer than a thorough understanding of the molder's art. Sand, the material almost universally used for molds, cannot be molded into any conceivable shape, but has certain practical limitations. For the most part, the impression in the sand of the mold is made by a pattern which must be so designed that its removal from the mold is possible. It is not as easy as it may first appear to avoid shapes which would call for a pattern which could not possibly be removed, leaving the mold intact. Another consideration is that sand, when confined, is a comparatively unyielding material, and therefore the shape of castings must be such that the shrinkage which invariably occurs as the metal cools will not induce dangerously high internal stresses.

Without mentioning any of the other factors it will be clear that the definite limitations of the molder's art constitute certain limitations for the engineer, and without a practical knowledge of the former iron castings cannot be intelligently designed.

344. Molds and Molding. The various methods of making sand molds may be divided into the following three classes of greatest importance: " green-sand molding " involves the making of an impression of the desired form, by means of a pattern, in a mold composed entirely of sand in a damp state; " dry-sand molding " involves the making of molds in damp sand by means of a pattern as in green-sand molding, after which the mold is dried in an oven until the moisture is expelled and the sand baked hard; " loam molding " does not involve the use of patterns, but its application is largely confined to articles whose surface are surfaces of revolution, the molds being built up of brickwork covered by a layer of loamy sand in which the desired imprint is made by a " sweep." Machine molding may replace hand work by either of these methods.

345. Green-sand Molding. Green-sand molding is employed in all foundries for the making of the great majority of all classes of iron castings. The exception is very large work which can be handled with greater safety by the dry-sand or loam methods.

The sand used for green-sand molding varies according to the particular usage to be made of it. In general it should be a mixture of silicious sand and some binder such as clay. The silica gives it a refractory character, while the alumina, in addition to its refractory character, acts as a binder to the sand. The amount of binder should be only sufficient to give the sand cohesiveness without causing it to bake into a nonporous mass which will not permit the gases to escape. The sand should in general be sharp and should be of finer grain for small castings than for large castings. It is used over and over, and needs only gradual replacement. Enough water to give it a proper consistency must be well mixed in after each time the sand is used.

With the exception of a limited class of castings such as plates, etc., molds are made in open frames of wood or iron called " flasks." The flasks usually consist of two parts (sometimes three or more), so provided with projecting pins and sockets that they may be taken apart and then returned to exactly the same relative position as before. The lower part of the flask is called the "drag," while the upper portion is called the "cope." Fig. 169 shows the type of flask commonly used with good-sized castings. Smaller flasks are not usually provided with the extension handles nor with the crossbars which are required to prevent the sand dropping out of large flasks during handling. Fig. 170 shows a type of flask called a "snap-flask" commonly used for small work. With this type the flask is removed from the mold after the latter is completed and is used over again instead of remaining until the metal has been poured. Fig. 171 shows most of the tools used in hand molding.

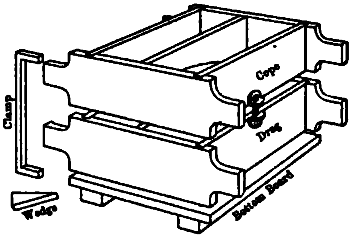


FIG. 169.—Flask for Green-sand Mold.

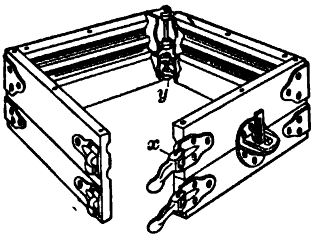


FIG. 170.—Snap Flask.

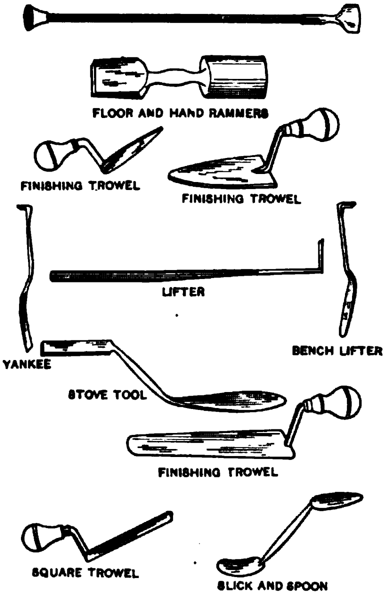


FIG. 171.—Tools Used in Hand Molding. (Stoughton.)

346. Patterns and Cores. Pattern-making is an art in itself involving a considerable amount of technical skill. It will therefore be here possible only to mention briefly a few of the considerations affecting the making and use of patterns.

Patterns may in general be divided into two classes, the first of which are used to produce solid castings, the second to produce hollow castings. In most cases, however, the pattern is solid, the hollow portion being formed by a "core" which is placed in the mold after the removal of the pattern.

The great majority of all patterns are made of wood. Brass or other metals are sometimes used, however, for the sake of greater durability when a great many molds are to be made from the same pattern. The simplest patterns are merely solid wood duplicates of the desired castings except that an allowance of about $\frac{1}{8}$ inch per foot is made in dimensions to compensate for the shrinkage of the castings in cooling. Fig. 172 (*a*) shows a simple turned pattern which is a duplicate of the casting except for the allowance for shrinkage and, in addition, a slight tapering of the vertical plane surfaces in order to facilitate the withdrawal of the pattern from the mold. The taper is indicated by the dotted lines; it is called the draft of the pattern and, on the average, amounts to about $\frac{1}{16}$ inch per foot. Such a pattern is not easily molded because of the necessity of arranging a parting of the mold on a diametral plane of the pattern in order that the latter may be withdrawn from the sand.

The same mold may be made much more easily by making a "parted pattern,"

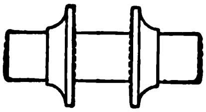


Fig. 172*a*.—Simple Turned Pattern.

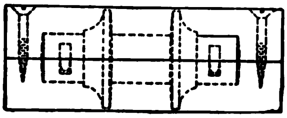


Fig. 172*b*.—Simple Parted Pattern.

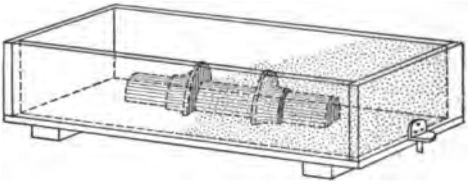


Fig. 172*c*.—Green-sand Molding. 1st Stage.

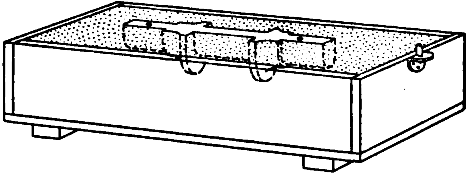


Fig. 172*d*.—Green-sand Molding. 2d Stage.

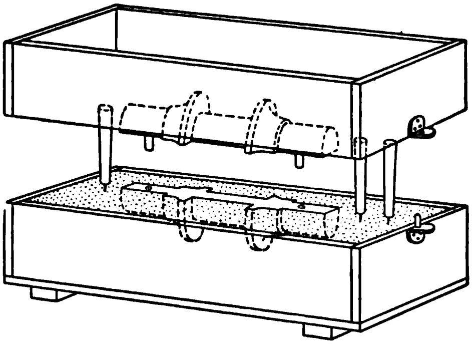


Fig. 172*e*.—Green-sand Molding. 3d Stage.

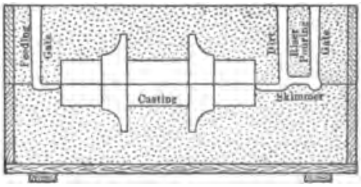


Fig. 172*f*.—Green-sand Molding.
Section of Finished Mold.

turned from two separate pieces of wood clamped together as shown in Fig. 172 (*b*). The two halves of the pattern after completion are fitted with "dowels" which hold them in the proper relation the one to the other. In order to improve the appearance of castings as well as save the molder extra trouble and obtain stronger castings it is always necessary to avoid all sharp angles in making patterns. This is done by rounding off all outside corners and placing a "fillet," Fig. 173, on the inner corner. Fillets are cut from wood or leather and glued in place, or else beeswax is used, the fillets being fashioned in place by a hot fillet iron.

FIG. 173.—Use of Fillets in Pattern Making.

FIG. 174*a*.—Cast-iron Flanged Tee.

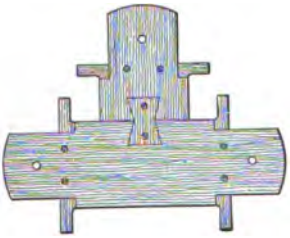


FIG. 174*b*.—Pattern for Flanged Tee.

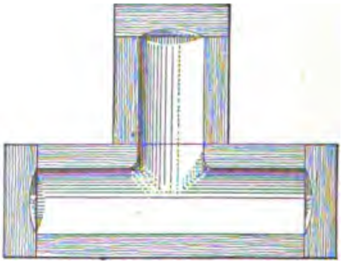


FIG. 174*c*.—Core Box for Flanged Tee.

When a core is used to obtain a hollow casting the pattern must be provided with "core-prints." These are simply projections beyond the pattern proper, built integral with the pattern. The prints form impressions in the mold which will subsequently be filled by extensions on the core. The cores will thus be supported in place in the mold. Fig. 174 (*b*) is the form of the pattern required for molding the flanged tee shown in Fig. 174 (*a*). Fig. 174 (*c*) shows the "core-box" in which the required core is molded.

The cores are usually made from a mixture of fine silicious sand with clay or loam, which is packed in the core-box while damp. Some binder such as flour and water, rosin, or glue-water, is usually required to give the core strength enough to permit handling, and holes are usually left running lengthwise through the core for the purpose of venting (allowing escape of gases). When the cores are dried in an oven prior to use in a mold they are called " dry-sand cores." The great majority of all cores are of this class. If a core is long, particularly if it is supported horizontally over a considerable span, it is necessary to stiffen the core by insertion of iron or steel wires or even skeleton frames of metal. Cores which are adjacent to thick parts of a casting are apt to be fused, unless protected from the heat of the slowly cooling molten metal. They are therefore often daubed with an insulating coating of " blackening." For this purpose pulverized graphite or plumbago is either applied wet as a wash, dry with a brush, or shaken from a cloth bag.

347. Making a Mold in Green-sand. The general features of green-sand molding may perhaps be best indicated by a description of the process of molding such a pattern as is shown in Fig. 172 (*b*).

One-half of the pattern is placed upon the molding board within the "drag" of the flask, the latter being placed upside down. Sand is now sifted into the flask until the pattern and molding board are well covered, after which unsifted sand is shoveled in and carefully packed and rammed until the flask is filled (Fig. 172 (*c*)). The top is struck off with a straight-edge and covered with a " bottom board." The molder now lifts the flask and turns the mold over, replacing it on his bench in the position shown in Fig. 172 (*d*), the bottom board and molding board being held in place by clamps during the operation of "rolling over." The molding board is now removed and the surface is "sleeked" over with a trowel to give it a fine finish. "Parting sand" (usually obtained by fine screening of the burnt sand cleaned from the castings) is now sprinkled over the surface to prevent adhesion between the two bodies of damp molding sand, the upper portion of the pattern is put in place, and the cope is fitted to the drag.

At this stage it is necessary to make provision for the admission of the molten iron and usually also for the removal of the slag and dirt. "Sprue-pins" (Fig. 172 (*e*)), consisting simply of cone-shaped pieces of wood whose lengths correspond to the depth of the cope, are placed in the cope at a proper distance from the pattern, the pins being held in place by a projecting pointed wire which is thrust down into the sand of the drag. The sand is now packed into the cope in exactly the same manner as was done with the drag, the sprue-pins are withdrawn, the cope lifted off, and the pattern carefully rapped and drawn. Any imperfections are now patched up and sleeked down, and a coat of blackening (usually graphite) is applied to the surface of the sand where imprinted by the pattern. The gates must now be cut connecting the mold with the riser and the pouring- and feeding-gates, after which the mold is "vented" by thrusting a vent wire into the sand at frequent intervals all around the mold, each vent being connected by a channel with the outside of the mold. These vents tend to permit the escape of gases generated when the castings are poured. The section of the finished mold will now appear as shown in Fig. 172 (*f*). (Often on small castings like this one the dirt riser may be omitted, the feeding gates being depended upon to serve a double purpose). After completion of the gate, cutting and venting, the cope is replaced and clamped to the drag and the mold is ready for the molten metal.

348. Dry-sand Molds. Dry-sand molding is applied principally to the making of rather large castings, especially when smooth surfaces are required. The lesser degree of skill required in making molds in dry sand permits the employment of inferior workmen. Less gas and vapor are generated when the mold is poured than is the case with green-sand, therefore necessitating less careful venting of the mold. Wooden flasks cannot be used in dry-sand molding on account of the fact that the molds are thoroughly dried in ovens at a temperature of from 150° to 200° C.

The sand required for dried molds must be of a more loamy nature than that used in green-sand molding, and in ramming the mold less care need be exercised to attain just the required degree of hardness. The manner of making the dry-sand mold differs little from the above described method of molding in green-sand, except in the matter of ramming and venting above noted.

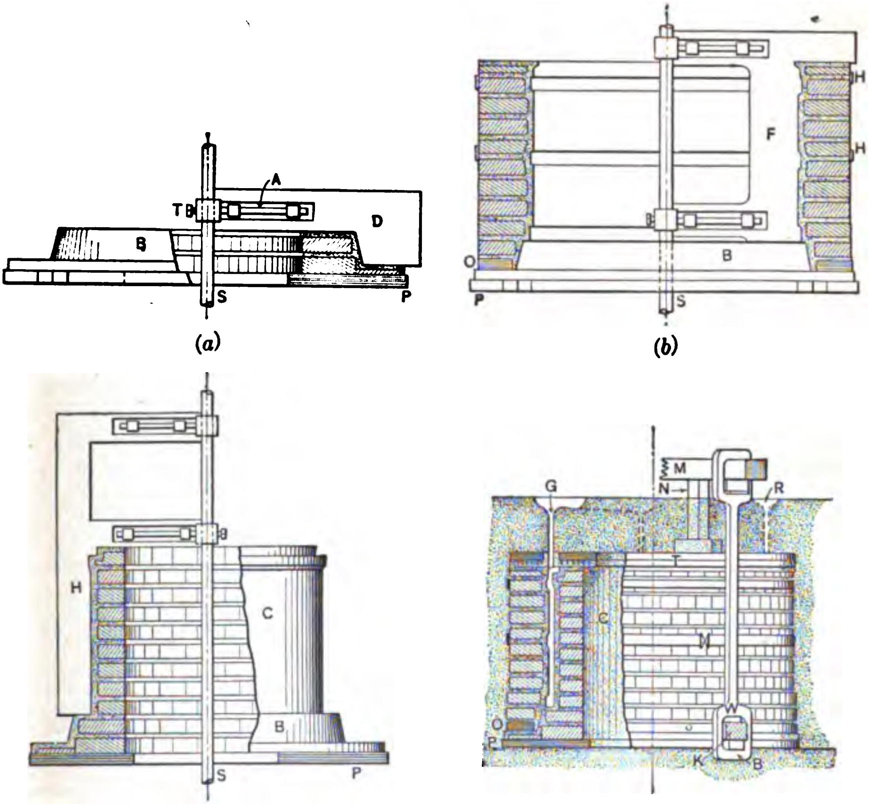
Drying the mold has the effect of driving off the moisture and leaving a firm, hard, semi-baked mass. The ovens are heated by coke, coal, or gas, and the temperature is carefully controlled to prevent burning and consequent crumbliness, or under-baking and consequent softness. The time required for oven drying is dependent upon the size of the mold. Small molds may perhaps be dried in an hour, while some large molds may require a day or more.

Dry-sand molds have the advantage over the green-sand in that less skill is called for in the making. They are stronger, and therefore the danger of sand-holes caused by the inclusion of loosened molding sand in the casting is less, also there is less danger of the mold yielding under the pressure of the molten metal. Furthermore, they tend to produce sounder castings, owing to the fact that far less gas is generated at the time of pouring.

On the other hand, the dry-sand mold is apt to shrink and become distorted during the drying; there is more danger of excessive cooling stresses and possible checking of the castings, due to the lesser degree of yielding of the sand as the cooling metal contracts; minor repairs to the mold are less easily made; and considerable extra expense is involved in the extra time and labor of handling in drying.

349. Loam Molds. The use of loam molds is restricted largely to that class of large castings whose surfaces are surfaces of revolution, the expense of the method not being justified as a rule under other circumstances. Exceptions to the rule are a few special classes of castings, such as gear wheels, where, by the use of special machines, the mold may be formed in loam with a considerable saving by reason of the fact that the making of a complicated pattern is unnecessary.

To explain the general features of loam molding the making of a mold for a hollow cylindrical casting will be described. The first step in the process consists in cutting boards in such a way that, when bolted to projecting arms mounted on a vertical spindle, their edges constitute elements of portions of the cylindrical surface of the finished casting. Those boards are called "sweeps" or "loam-boards" (*D* Fig. 175 (*a*), *F* Fig. 175 (*b*), *H* Fig. 175 (*c*)), and it will be evident that when the sweep is rotated about the spindle its edge will generate the desired cylindrical surface. The steel "bottom-plate" (*P* Fig. 175 (*a*)) is leveled up on blocking, the spindle seat is embedded in the floor in a central position, and the spindle set up and its bearing adjusted. The molder now constructs the foundation and base of the mold by laying up a brickwork ring which is cleared by the sweep by about ½-inch on all sides. Loam, and not mortar, is used in laying up the brickwork. The joints are sometimes filled with fine cinders to aid in venting the mold. A coarse loam mixture is now daubed on the brickwork and the entire surface is swept up. A finishing coat of fine loam is next applied, and the sweeping continued until the surface has a smooth finish. Finally the entire base is lifted and taken to an oven and dried.



(*a*) (*b*)

(*c*) (*d*)

Fig. 175.—Successive Operations in Making a Loam Mold. (Bale.)

The "lifting ring" (*O* Fig. 175 (*d*)) is now laid on the bottom plate outside the base of the dried mold and the brickwork of the "cope" (*H* Fig. 175 (*d*)) is laid thereon, the sweep *F* having replaced the one used for the base. After each few courses of brick are laid the loam mixture is daubed on and swept up and finished as before. When the cope is complete, chains are hooked into the lifting plate, and the cope is lifted off the base by a hoist and moved to the oven while the "core" is being built. The sweep and spindle have been removed during this last operation. The spindle is now replaced and the cope-sweep is replaced by the core-sweep (*H* Fig. 175 (*c*)). The core is now built up in the same manner as was the cope, after which the spindle is finally removed, the core is dried and replaced on the base, and the cope lifted back into place. The top plate (*T* Fig. 175 (*d*)) is now lowered into place. This plate is studded with projections which hold in place a layer of loam which has been applied and dried on beforehand. Holes in which sprue-pins are inserted (*G* Fig. 175 (*d*)) are provided at intervals in the plate to provide pouring gates and risers. The inside of the core is now filled with sand, and more sand is rammed to a depth of a foot or more on top. Finally a circular runner is cut in this sand to connect the several pouring gates, the sprue-pins are removed and the mold is ready for pouring.

Such castings as the one described are sometimes so molded in a sectional loam mold that the mold need not necessarily be destroyed in removing the castings. In this event the mold may be used for several castings with only minor repairs.

350. Chilled Castings. A "chilled casting" is one made in a mold, some parts of which, at least, are made of iron, such portions of the mold being called "chills." The purpose of introducing chills into a mold is to convey away the heat of the molten metal rapidly, a treatment which, for reasons to be discussed later, has the effect of causing the carbon in the iron to remain in chemical combination, instead of separating therefrom in the form of graphite, as it normally does in slowly cooled castings of gray iron. The physical effect of chilling on the character of the iron is to greatly harden it for a certain depth, giving to the exterior of the iron the characteristic appearance of white iron, while the body of the casting remains a gray iron.

Chilling is principally used for wearing surfaces of such castings as iron rolls and treads of car wheels. The manner of molding chilled castings differs in no respect from the methods above described except in the interposition of the chills in the mold. The dry-sand method of molding is most commonly used. Fig. 176 shows the manner of introducing chills to harden the tread of a car wheel. It is often difficult to secure the depth of chill desired (often $\frac{3}{4}$ inch or more) on account of the shrinkage of the casting and the expansion of the chill. On this account several special types of sectional chills have been devised, their arrangement being such that they may be made

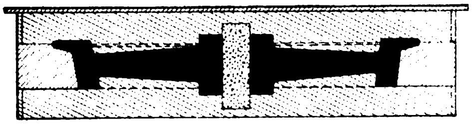


FIG. 176.—Use of Chills on Treads of Car Wheels.

to contract as the casting contracts, thus keeping in contact therewith for a longer period. Chilled castings are allowed to cool till near atmospheric temperature before being removed from the mold, or else they are removed as soon as they are solid, and placed in annealing pits where they are cooled still more slowly for a period of two or three days. This slow cooling has the effect of relieving internal stresses caused by the non-uniform rate of cooling in the mold.

351. Pouring the Iron. In small foundries it is usually the practice to stop molding in the middle of the afternoon and pour off all the molds that have been made. For small work the metal is caught in hand ladles at the cupola tap-hole and conveyed to the molds by one or two men. The ladles must be heated by allowing a part of the first iron run to stand in them for a few moments before the actual pouring is begun. Otherwise the ladle will chill the metal and the iron will not enter the mold at the required temperature. Practically all foundry ladles are " top-pouring " (i.e., the metal is poured by tipping the ladle), rather than " teeming " ladles, which are provided with a valve in the bottom. This necessitates the use of a bar to keep back the slag which floats on the metal and would otherwise enter the mold. Care is exercised by the molder to hold the ladle as near the pouring gate as possible to lessen the impact of the stream of metal upon the sand of the mold. The proper time to cease pouring is indicated by the appearance of the metal at the top of the riser. Each mold must be filled in one operation, and therefore when the ladle does not contain enough metal to completely fill a mold its contents are emptied into pig-beds molded on the foundry floor.

Larger foundries employ traveling cranes and large ladles holding perhaps a ton or more of metal. The ladles are, however, of the top-pouring type. During the filling of the molds, it is usually the practice to ignite the gas which escapes from the vent holes, thereby preventing accumulation of the gas in the molding room.

The flasks are removed soon after the completion of the pouring, and the molds are dumped off the bottom boards in piles, from which the hot castings are hooked out and allowed to cool. The gates and runners are now broken off by a few sharp blows with a hammer and the castings removed for cleaning.

352. Cleaning the Castings. The sand which adheres to the castings is usually removed by one of three methods: rattling them in a " tumbling barrel," pickling, or sand blasting.

Rattling is most commonly practiced in case of small castings. The tumbling barrel is simply a short horizontal cylinder which is mounted on trunnions, Fig. 177. The castings are piled into the barrel, together with a quantity of abrasive material in the shape of small, irregularly shaped, hard iron "stars" or "picks." The barrel is rotated slowly and the falling about of the castings and the stars gradually knocks the burnt sand and scale off the surfaces of the casting. This method has the disadvantage of producing a hard skin upon the castings which causes difficulty if they are subsequently to be machined.

Rattling will never completely clean any but very simple castings, and a better method consists in pickling the castings by immersion in a dilute sulphuric or muriatic acid solution. The acid attacks the iron somewhat, thereby loosening the sand and scale. Pickling in a 15 per cent solution of sulphuric or muriatic acid requires about twelve hours and must be followed by a careful washing in water. Hydrofluoric acid now sometimes replaces sulphuric or muriatic acid. The former attacks the sand itself, instead of the iron, and with only about a 5 per cent solution castings may be cleaned in an hour or less.

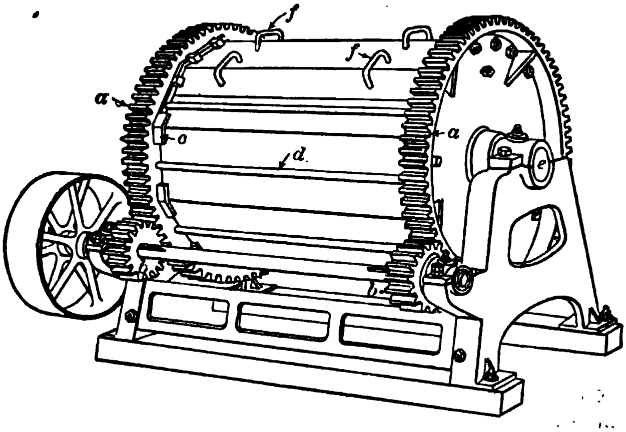


Fig. 177.—Tumbling Barrel.

The sand blast is the most convenient method of cleaning large castings, especially those of very irregular form, such as gears, etc. Very often the sand blast is followed by pickling.

The final operation in the preparation of castings for use consists in smoothing up the irregularities left by breaking off the gates, the "fin" formed where the metal has run between the two portions of a mold, etc. With small castings this is most readily done with an emery wheel; even a file may be used. With larger castings chipping with a cold chisel is often necessary, and a pneumatic chipping tool is most efficient. Portable emery wheels fitted with a flexible drive are now sometimes used for this purpose.

PROPERTIES OF CAST IRON

CONSTITUTION

353. Essential Constituents of Cast Iron. The composition of cast iron is that of a complex alloy containing usually six important elements, together with other elements of less frequent occurrence. The elements invariably present are, in the approximate order of their importance, iron, carbon, silicon, phosphorus, sulphur, and manganese. In addition, copper, nickel, oxygen and nitrogen are often present, and aluminum, titanium, and vanadium are sometimes added.

The constitution of cast iron is much more complex than the composition, because of the variety of compounds which the elements present combine to form. The most important consideration affecting the character and properties of cast iron is the carbon content and, in particular, the form assumed by the carbon, i.e., whether free as graphite, or in chemical combination with the iron as a carbide. The importance of the elements other than the iron and carbon is chiefly due to their influence upon the state assumed by the carbon.

Before we can state even in a general way the essential constituents of cast iron we must recognize the existence of three principal classes of cast iron, the difference in character being due to the different states in which the carbon occurs.

Gray cast iron is that in which the carbon occurs chiefly in the graphite state.

White cast iron is that in which the carbon occurs chiefly as the carbide of iron.

Mottled cast iron is a mixture of particles of gray iron with particles of white iron.

The essential constitution of gray iron is that of an aggregate of very impure " steel " mechanically mixed with graphite. The matrix which we speak of as " steel " has two main constituents, " ferrite " and " cementite." Ferrite is that part of the steel which is practically pure iron, containing only a trace, or even no carbon in solid solution. Cementite is a definite carbide of iron having the formula Fe_3C.

White cast iron has the constitution of very high carbon steel except for the great amount of impurities present. It consists of a large amount of cementite together with a small amount of " pearlite," the latter being a certain mixture, of a more or less definite composition, of ferrite and cementite.

354. Carbon in Cast Iron. When cast iron solidifies from the molten state the carbon probably remains in the combined condition as carbide of iron, Fe_3C, which is partly free as cementite and partly in solid solution in the iron as "austenite."* The Fe_3C is an unstable compound, however, and when formed at a high temperature is readily decomposed into graphite and iron.

The decomposition of the carbide with the consequent formation of graphite carbon is facilitated particularly by a slow rate of cooling and by the presence of silicon. It is retarded, on the other hand, by rapid cooling or by the presence of much sulphur or manganese.

355. Gray Cast Iron. Cast irons containing considerable amounts of graphite carbon are known as gray cast irons, because of the grayish or blackish coarsely crystalline appearance of their fractures. This appearance is caused by the presence of many irregular and generally elongated and curved plates of graphite imbedded in the matrix of ferrite and cementite. These plates of graphite are made up of smaller plates, somewhat like sheets of mica, and may be split apart with ease. The individual sheets of graphite vary in size from microscopic proportions to one-eighth of a square inch or more in area. The characteristic structure of gray cast iron when highly magnified is shown in the photomicrograph of Fig. 178. The irregular dark bands are graphite plates, the intermediate area being the ferrite-cementite matrix. The actual percentage by weight of graphite in gray cast iron will be between 2 and 4 per cent, the amount of combined carbon being under 1½ per cent. The volume content of graphite is much higher, however, since iron has a specific gravity about three and one-half times that of graphite. The volume content of graphite will, therefore, amount to from 7 to 14 per cent.

FIG. 178.—Gray Cast Iron.
Magnified 100 Diameters. (Boylston.)

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* See page 422 for an explanation of the term "solid solution," and page 430 for a definition of "Austenite."

The great difference in the character of gray iron and white iron is readily seen to be due primarily to the following considerations: The presence of much graphite means that little iron carbide, which is very hard and possessed of great physical strength, will be present. At the same time the occurrence of weak and soft but tough ferrite is increased, and lastly, the graphite itself is weak and forms a more or less complete mesh separating the matrix into partially isolated particles to which it adheres very slightly. It is therefore to be expected that gray iron will be soft and weak, although comparatively tough, while white cast iron is hard and strong but brittle and difficult to work.

356. White Cast Iron. Cast iron, the bulk of whose carbon is present in chemical combination with iron, as carbide of iron (Fe_3C), or cementite, is called white cast iron because of the white, highly metallic fracture which characterizes it. As noted above, the ferrite and a portion of the cementite together form pearlite, so that the ultimate constitution of an iron free from graphite will be a mixture of cementite and pearlite. Pearlite is a mixture of cementite and ferrite, the two components occurring most commonly as small wavy or parallel plates of alternately light and dark color. The characteristic appearance of laminated pearlite under high magnification is shown in Fig. 179. Ferrite and cementite combine in rather definite proportions to form pearlite the proportion of carbon to pure iron being 1 : 120. The appearance of white cast iron when highly magnified is shown in Fig. 180, wherein the light areas are free cementite, while the dark-banded areas are pearlite.

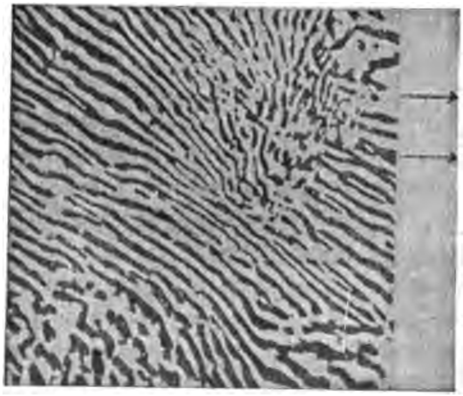

FIG. 179.—Pearlite.
Magnified 1000 Diameters. (Osmond.)

While white cast iron is structurally not distinct from very high-carbon steel, if the occurrence of larger amounts of elements other than iron and carbon is disregarded, it lacks entirely the malleability of steel and is extremely hard and brittle because of the presence of a very large proportion of the hard and brittle free cementite. The dividing line between high-carbon steel and white cast iron lies at about 2.2 per cent carbon but, as a matter of fact, most steels do not approach 2 per cent carbon and few white cast irons have less than 2.25 per cent or even 2.50 per cent carbon.

357. Mottled Cast Iron. Irons which contain particles of gray cast iron mixed with particles of white cast iron, and which are therefore non-homogeneous in character, are sometimes produced. Such irons are called mottled cast irons. They have no special adaptation, and their production is largely unintentional. The microscopic structure of such an iron is shown in Fig. 181.

FIG. 180.—White Cast Iron. Magnified 500 Diameters. (Wust.)

FIG. 181.—Mottled Cast Iron. Magnified 500 Diameters. (Wust.)

358. Silicon in Cast Iron. After iron and carbon, silicon is, in its effects upon the character of the iron, the most important element present in cast iron. We have seen that the amounts of silicon and sulphur retained in pig iron are under the more or less complete control of the blast-furnace manager, and the amounts present in cast iron are similarly under the control of the foundry manager. The content of carbon and phosphorus, on the other hand, is not under control, nor is that of manganese, except to a slight extent. Silicon and sulphur, however, have a marked effect upon the condition of the carbon and, in consequence, they exert a powerful influence upon the properties of iron.

Silicon combines with a part of the iron to form silicides (Fe_2Si, FeSi, etc.), which dissolve in the ferrite portion of the iron. Silicon's primary effect upon the carbon is as a precipitant, driving the carbon out of combination into the graphite form. The maximum precipitation of graphite seems to occur with about 2.5 to 3.5 per cent of silicon, and when the silicon exceeds this limit the effect is reversed, the proportion of combined carbon or cementite being increased.

Silicon in percentages below about 3.0 per cent acts, therefore, as a pronounced softener, producing soft gray iron, but larger percentages result in the formation of hard and brittle white iron. Small percentages also produce freedom from oxides and blowholes, promote fluidity, and decrease shrinkage and depth of chill.

359. Sulphur in Cast Iron. The influence of sulphur upon the form assumed by the carbon in cast iron is exactly the reverse of the influence of silicon. That is, the higher the sulphur content, the higher will be the proportion of combined carbon. This tendency upon the part of sulphur is much more potent than is the opposite tendency exhibited by silicon, however, a given amount of sulphur being able to neutralize about fifteen times as much silicon. Sulphur therefore tends to produce hard, brittle, white iron.

Aside from the effect of sulphur upon the character and properties of iron consequent upon the fact that the carbon is driven into combination as the carbide, cementite, sulphur inherently possesses the power to materially affect the behavior of iron in solidifying and cooling. Only a few tenths of 1 per cent of sulphur suffices to render iron very tender at a red-heat ("red-short"), and therefore apt to check or crack if in solidifying the shrinkage causes the casting to tend to crush the sand of the mold, thus resulting in the setting up of internal stresses in the iron. Sulphur also causes solidification to become very rapid, and often is responsible for the presence of blow-holes and sand-holes.

Manganese, because of its great affinity for sulphur, will tend to rob the iron sulphide, FeS, of its sulphur, forming MnS, which latter compound is much less potent than FeS in affecting the proportion of combined carbon. A given percentage of sulphur may, in general, be neutralized by the presence of about twice as much manganese. Specifications usually limit the maximum sulphur content of gray cast iron to not over 0.10 per cent and often the maximum allowance does not exceed 0.05 per cent.

360. Phosphorus in Cast Iron. The effect of phosphorus upon the state assumed by the carbon is rather self-contradictory; chemically, it tends to increase the proportion of combined carbon, especially when the silicon is low and the phosphorus high. On the other hand, phosphorus lengthens the time of solidification, thereby affording additional opportunity for the precipitation of graphite. When the silicon is high, therefore, the presence of moderate amounts of phosphorus actually increases the precipitation of graphite, but when the proportion of phosphorus is very large, the chemical effect is great enough to retain the carbon in the combined form in spite of the longer period of solidification.

The presence of phosphorus in considerable amounts tends therefore to produce a hard white iron, lacking in toughness and workability, and especially lacking in shock resistance when cold. Phosphorus reduces the melting-point of iron and makes it very fluid. It is therefore useful in making very thin castings where a less fluid iron will not take a perfect impression of the mold. Not more than 0.05 per cent of phosphorus is allowed in best gray iron, while from 1.0 to 1.5 per cent is sometimes used when fluidity is more important than toughness.

361. Manganese in Cast Iron. Manganese increases the total carbon content of cast iron and also increases the proportion of combined carbon, though it is much less potent in this latter respect than is sulphur.

As above noted, however, the effect of manganese cannot be considered apart from that of the sulphur. If no more manganese is present than is required to combine with the sulphur, forming MnS, its effect will not be to increase the proportion of combined carbon, but will be just the reverse, because the sulphur is taken from the sulphide, FeS, which is so powerful in causing the carbon to assume the combined form. Any additional manganese unites with carbon to form the carbide Mn_3C, and this carbide unites with the Fe_3C, causing the cementite to be made up in part of the double carbide of iron and manganese $(FeMn)_3C$.

It appears, therefore, that manganese up to the amount which combines with sulphur to form MnS tends to lower the proportion of combined carbon and consequently decreases the hardness and brittleness of the iron. Any additional manganese, however, has a marked effect in causing the carbon to assume the combined form, and is therefore a hardener.

Large percentages of manganese are sometimes added to cast iron designed for use as "spiegeleisen" or "ferromanganese" in steel making, but for ordinary castings the manganese seldom exceeds 2 per cent and may be as low as 0.10 per cent.

BEHAVIOR OF IRON IN COOLING.

362. Shrinkage. The shrinkage of cast iron is an important consideration for the pattern maker, because due allowance for shrinkage must be made in the dimensions of the pattern if the casting is to conform to the size called for by the drawings. It is also an important consideration for the designer and the founder, because the stresses set up in cooling and the consequent danger of checking are directly dependent upon the degree of shrinkage if the casting be of such a shape that its shrinkage tends to crush the sand in the mold.

All metals expand upon heating and contract when cooling, and the total expansion in melting a metal will correspond to its total shrinkage in solidifying and cooling. Pure iron shrinks about 0.3 of an inch per foot; a less pure iron usually shrinks less, because impurities, particularly carbon, usually lower the melting-point.

In addition, the separation of carbon as graphite exerts a powerful influence upon the total net shrinkage of iron because of the expansion which its separation causes.

The factors which chiefly determine the amount of shrinkage are therefore the factors which chiefly control the separation of graphite, i.e., the silicon content and the rate of cooling. Moreover, since the latter is largely dependent upon the size of the castings, the shrinkage becomes largely a function of silicon content and size. This relationship is shown graphically by Fig. 182, which is based upon experiments made by W. J. Keep.* The shrinkage is shown to be inversely proportional to the per cent of silicon, and for an iron of given composition the shrinkage decreases as the size of casting increases.

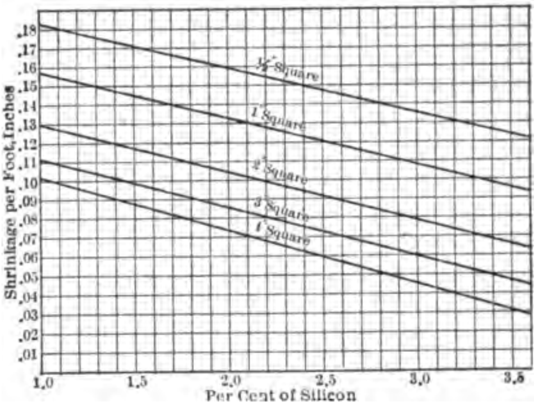

Fig. 182.—Approximate Relationship Between Shrinkage, Silicon Content, and Size.

Other elements whose presence affects the separation of graphite, either directly or by affecting the rate of cooling, naturally have an effect upon shrinkage. Sulphur, which drives carbon into combination with iron, therefore increases shrinkage unless neutralized by other elements. Manganese increases the total carbon and also the proportion of graphite if not present in amounts sufficient to provide an excess over that required for combination with the sulphur. It therefore decreases shrinkage except when excessive amounts are present. Phosphorus by lowering the rate of cooling tends to promote the separation of graphite and decrease the shrinkage. The separation of an iron phosphide from the solid solution near the point of solidification also causes an expansion, as is the case when graphite separates. This circumstance, therefore, increases the effectiveness of phosphorus in decreasing shrinkage.

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* W. J. Keep, "Cast Iron," p. 48.

363. Checking. Liability upon the part of iron to check while cooling is dependent upon the magnitude of the stresses caused by the contracting of the metal upon the sand, and upon the weakness of the metal at a temperature slightly above a black heat (the temperature at which checking usually occurs). The factors which govern shrinkage, therefore, determine the stresses to which the cooling metal will be subjected, if the casting be of such a shape as to compress the sand in shrinking.

Sulphur is the most deleterious element affecting the strength of iron at a temperature just above a black heat. At this temperature both the iron sulphide and the magnesium sulphide are still in a pasty condition, thereby causing weakness of the metal. Phosphorus, by decreasing shrinkage, should decrease the liability of the metal to check, but this effect may be more than offset by the tendency of phosphorus to cause the metal to assume a coarsely crystalline structure. Manganese tends to counteract this last tendency upon the part of the phosphorus and therefore tends to prevent checking.

364. Segregation. Segregation in castings is the collecting together of impurities in spots. The primary cause of segregation is the effect of impurities in lowering the freezing-point of iron. This results in forming a fluid solution which remains molten after the remainder of the metal has solidified, and which runs to that part of the casting which has the loosest texture. These spots, often called " hot spots," are apt to occur in the middle of the larger sections of the casting. They are often porous, and are usually extremely hard and brittle.

The tendency to segregation is proportional to the amount of impurities present. Phosphorus is especially apt to cause segregation, and manganese and sulphur have the same effect to a less marked extent. Segregation is not a commonly encountered difficulty in iron founding, however, since other considerations will usually require a degree of freedom from excessive amounts of phosphorus, sulphur, or manganese which will minimize the danger of segregation.

365. Chilling. The intentional chilling of iron by the insertion of metal chills in a mold has been discussed above in Art. 350. The production of properly chilled iron is a very difficult problem, mainly on account of the effect of variations in composition of the iron upon the depth of chill obtained. The most important factors in this regard are the contents of silicon and of sulphur. If the silicon is comparatively high and the sulphur very low chilling is practically impossible. If both silicon and sulphur are very low a considerable amount of chill is obtained, and the best results are obtained when a low percentage of silicon is combined with a rather high percentage of sulphur. Phosphorus and manganese have little effect upon the depth of chill; the latter, however, increases the hardness of the chilled iron.

PHYSICAL AND MECHANICAL PROPERTIES

366. Hardness. The precise meaning of the term hardness as applied to metals is not altogether fixed. Properly, hardness should be considered simply the measure of the resistance of the metal to being cut or scratched by a tool, or to being worn away by abrasion. Tenacity and brittleness are properties which are quite distinct from hardness, yet many methods employed for measuring hardness do not recognize any distinction.

The principal factor in determining the hardness of cast iron is the amount of combined carbon. This is due, first, to the hardness of cementite itself, and second, to the fact that increase in combined carbon usually means a decrease in graphite carbon, which is very soft. (Graphite has a further effect in increasing the ease with which cast iron may be worked, because it acts as a lubricant for the cutting tool.)

The influence of elements other than carbon upon the hardness of iron is, with the exceptions of manganese, directly dependent upon their power to increase the amount of combined carbon. Silicon, therefore, acts as a pronounced softener, unless its percentage exceeds about 3 per cent, when the effect is reversed. Sulphur and phosphorus act as hardeners in all percentages, and manganese, in addition to its indirect effect due to the formation of combined carbon, has a direct hardening influence owing to the hardness of the compound $(FeMn)_3C$.

TENSILE STRENGTH

367. Tensile Strength in General. The tensile strength of cast iron is dependent upon so many variable factors that no general statement may be made concerning it. The founding methods, the design, and the size of castings are always important factors influencing strength. In addition, the composition and, more particularly, the constitution exert an enormous influence upon strength.

The effect of details in founding methods, and the importance of design, etc., have been noted in a previous chapter. The effect of variations in composition and constitution is really a question of the state assumed by the carbon. No other factor can be considered to be nearly as important as the relative proportion of combined and graphitic carbon present, and the importance of elements other than carbon is largely in proportion to their power to either increase or decrease the proportion of combined carbon.

368. Influence of Form of Carbon. Gray cast iron has been represented to consist really of plates of weak, soft, wholly non-metallic graphite, forming a more or less complete mesh-work which separates the ferrite and cementite matrix into partially isolated particles. The cementite and ferrite matrix of gray iron is really a low- or medium-carbon steel, possessing great toughness combined with great softness, ductility, and low strength. White cast iron, upon the other hand, is a mixture of cementite and pearlite, not distinct from high-carbon steel except in the relatively greater impurity of the white cast iron, and the higher percentage of free cementite.

The presence of graphite plates in any proportion must necessarily decrease the strength of the steel matrix and, therefore, the strength of the iron as a whole, because the graphite breaks up the continuity of the steel matrix. This injurious effect of graphite is not necessarily directly proportional to the percentage of graphite present but, rather, is proportional to the degree of continuity of the graphite mesh.

Any diminution in the proportion of graphite will, in general, however, mean a diminution in some degree of the continuity of the graphite mesh and will, therefore, mean a lessening of its detrimental effect upon strength. At the same time, a diminution in the proportion of graphite means an increase in the proportion of combined carbon or cementite in the steel matrix. This increase in the proportion of cementite in the matrix means a proportionate increase in its strength until the percentage of cementite in the iron reaches a certain point, which is in the neighborhood of 1.2 per cent for an iron containing about 4.0 total carbon. Further increases in the percentage of cementite beyond this point increase hardness and brittleness at the expense of toughness, ductility, and strength. It is, therefore, evident that the strength of an iron will be greater when the percentage of combined carbon (cementite), does not exceed about 1.2 per cent than it will be if any higher percentage be present. Whether the highest strength is found with about 1.2 per cent cementite, or when the percentage of cementite is below this point will depend upon whether the loss of strength due to increase in graphite on the one hand, or the gain in strength due to the higher carburization of the steel matrix on the other hand, is the more influencial factor. This point cannot be settled on purely theoretical grounds, perhaps, but as a matter of common experience we know that the gain in strength of the steel matrix as the cementite content increases is really the controlling factor and, in consequence, the cast iron shows an increase in strength as the percentage of combined carbon increases up to about 1.2 per cent, after which further increases in combined carbon mean a loss in strength.

The whole substance of the above discussion is presented graphically in the diagram of Fig. 183, which is abstracted from the original of Professor Henry M. Howe. In this diagram it has been assumed that the iron possesses a constant total carbon content (4 per cent), and an effort has been made to show graphically in an approximate degree, the effect of varying the proportion of combined carbon upon tensile strength. (Both the above discussion and Fig. 183 must be taken simply as indicating roughly the normal relationship of form of carbon to tensile strength of cast iron.)

369. Influence of Metalloids and Rate of Cooling upon Strength. The influence of the metalloids and the rate of cooling upon the strength of castings is, as above noted, largely an indirect one, dependent upon the extent to which the separation of graphite is facilitated or retarded.

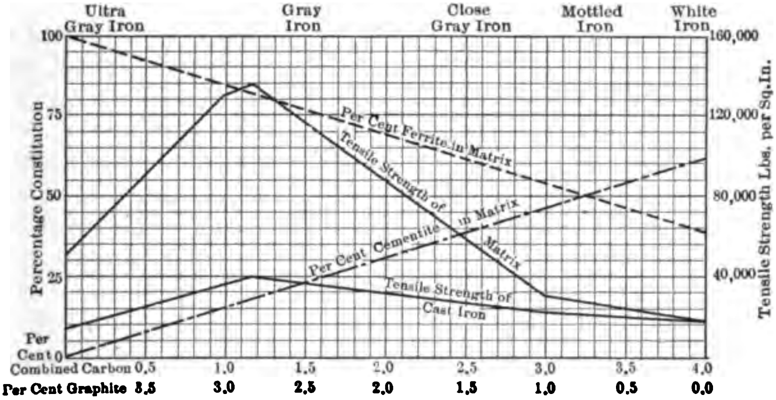

FIG. 183.—Approximate Relationship Between Tensile Strength of Cast Iron and State of Carbon. (Howe.)

Silicon in small amounts, by favoring the precipitation of graphite, exerts an influence which is beneficial to strength, provided that an excessive amount of combined carbon would otherwise be present. In this event the gain in strength of the matrix which accompanies the relief of brittleness more than compensates for the injurious effect of the increase of graphitic carbon. If, on the other hand, the additional graphite precipitation caused by silicon produces an iron whose matrix possesses too little combined carbon, the iron is weakened both because of the lowering of the strength of the matrix and because of the weakening and softening influence of the graphite.

Large amounts of silicon (above about 3 per cent) have been observed to have exactly the reverse effect upon the form assumed by carbon, the proportion of combined carbon instead of graphite carbon being increased. Therefore the effect of large amounts of silicon upon strength is exactly the reverse of the effect of small amounts above noted.

Aside from this indirect effect of silicon upon strength it possesses the power to increase strength directly,. due to the formation of compounds which strengthen the matrix. When the silicon exceeds about 4 per cent this effect upon strength is reversed, owing to the increased brittleness of the iron, and with all percentages of silicon, this direct effect is of much less consequence than the indirect effect above stated. The proportion of silicon desirable for strong castings is closely dependent upon the size of the casting and the content of total carbon, sulphur, manganese, and phosphorus. In large or slowly cooled castings, a maximum strength will be obtained when the silicon is low (only sufficient to offset the tendency of the sulphur and other metalloids to prevent the separation of graphite). In thin, quickly cooled castings, on the other hand, the silicon should be reasonably high, as should also be the case if the sulphur is high and not offset by manganese.

The influence of sulphur is always as a weakener of cast iron, not only because it prevents the separation of graphite chemically and by hastening solidification, but also because it promotes the inclusion of flaws (blowholes sand-holes, or shrinkage cracks), induces internal stresses, and causes coarse crystallization and brittleness. The baneful influence of sulphur may of course be more or less completely neutralized by much larger percentages of silicon or by the presence of about twice as much manganese.

Phosphorus usually tends to promote the formation of excess combined carbon and, therefore, to weaken cast iron. When the silicon is high, however, a moderate amount of phosphorus may, by increasing the time of solidification, promote the separation of graphite, as above explained, thereby improving strength. The presence of more than about 0.05 per cent phosphorus will, however, always be detrimental to strength.

The effect of manganese upon strength is always dependent upon the relative amounts of sulphur and manganese present. If the manganese content does not exceed twice the sulphur content, the manganese simply neutralizes the tendency of sulphur to decrease the proportion of graphite, and therefore the manganese increases strength. When the content of manganese exceeds the amount required to neutralize the sulphur, however, the excess manganese has a marked effect detrimental to strength because of the resultant excessive increase in the proportion of combined carbon.

370. Stress-strain Diagram for Cast Iron. It will be evident from the above discussion that cast irons must exhibit a great variability in elastic properties, since so many factors affect strength.

In Fig. 184 typical stress-strain diagrams for three radically different cast irons are presented in order to illustrate their usual behavior under tensile stress.

It will be observed that there is no well-defined elastic limit or yield point, but if we may consider the yield point to be the stress at which a marked increase in rate of deformation first appears, this point will be found to fall at about 60 per cent of the ultimate strength, except in the case of the soft gray iron, when it falls at only 25 or 30 per cent of the ultimate strength. For the typical irons shown in Fig. 184 the ultimate strength falls at 35,500 pounds per square inch for the hard gray iron, 22,500 pounds per square inch for the average gray iron, and 16,000 pounds per square inch for the soft gray iron. The yield points are found to fall at about 22,000 pounds per square inch, 14,000 pounds per square inch, and 5000 pounds per square inch, respectively.

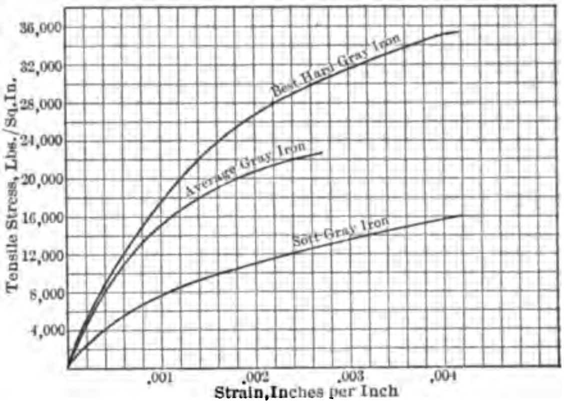

FIG. 184.—Stress-strain Diagrams for Cast Irons. (Tension.)

No constant proportionality of stress to strain exists for any considerable load interval, and therefore we cannot properly say that cast iron has a modulus of elasticity. If we consider, however, that the term may be applied to the ratio of stress increment to corresponding strain increment for successive small load intervals, we find that the value of *E* is initially about 30,000,000 pounds per square inch for hard cast iron, 24,000,000 pounds per square inch for average iron, and 14,000,000 pounds per square inch for soft iron. At 5000 pounds per square inch stress, the values of *E* have decreased to about 20,000,000 pounds per square inch, 15,000,000 pounds per square inch, and 7,000,000 pounds per square inch, respectively; and at 10,000 pounds per square inch stress, the values of *E* are about 15,000,000 pounds per square inch for hard iron and about 14,000,000 pounds per square inch for average iron. (The elastic limit of the soft iron has been exceeded at this stress.)

The percentage elongation is small for all cast irons, rarely exceeding from 3 to 4 per cent for any grade, and the reduction of area is usually too slight to be appreciable.

371. Specification and Allowable Stress. The specifications of the American Society for Testing Materials recognize a distinction in elastic properties between light, medium, and heavy castings. Castings having any section less than ½ inch thick are classed as light castings; castings having no section less than 2 inches thick are classed as heavy castings; and castings not included in either of the above divisions are classed as medium castings.

The minimum ultimate tensile strength of gray iron castings is not permitted to fall below:

18,000 pounds per square inch for light castings;
21,000 pounds per square inch for medium castings;
24,000 pounds per square inch for heavy castings.

The factor of safety usually employed in the design of iron castings is about seven. The safe working stress of cast iron in tension is therefore usually taken to be about 3000 pounds per square inch.

COMPRESSIVE STRENGTH

372. Compressive Strength of Cast Iron. The compressive strength of cast iron, as is the case with all comparatively brittle materials, is largely a function of the shearing strength, since failure will inevitably occur along an oblique plane unless the specimen tested is sufficiently long to permit failure by lateral flexure. (In the latter case, stresses other than pure compression contribute to the failure.)

The factors which control compressive strength are, however, exactly the same factors which control tensile strength. The most important consideration is, therefore, the state assumed by the carbon, and compressive strength will be benefited by all agencies which tend to increase the proportion of graphite carbon and decrease combined carbon, until the point of saturation of carbon in the steel matrix is reached (about 1.2 per cent combined carbon), beyond which point further increases in graphite mean a loss in strength of the matrix, and therefore a loss in strength upon the part of the iron as a whole.

Compressive tests of cast iron show an enormously wide variation in strength values. If large specimens such as structural columns, etc., be tested, the ultimate strength will seldom be found to exceed 30,000 to 40,000 pounds per square inch. If, however, short specimens of small size be tested, the strength will be found to run to from 50,000 to 150,000 pounds per square inch. (This discrepancy is doubtless largely due to inevitable hidden defects in the large sections.)

Three typical stress-strain diagrams for compression of short blocks of cast iron are presented in Fig. 185. It will be observed that the yield point is much more clearly marked in compressive tests of cast iron than in tensile tests, although no absolutely constant ratio of stress to strain is maintained for any considerable load interval.

The ultimate strengths of the three irons of Fig. 185 are 93,000 pounds per square inch, 63,000 pounds per square inch, and 44,000 pounds per square inch, for hard, average, and soft irons, respectively. The yield point falls at about 44,000 pounds per square inch for the hard iron, 30,000 pounds per square inch for the medium iron, and 20,000 pounds per square inch for the soft iron. The moduli of elasticity at 10,000 pounds per square inch are about 30,000,000 pounds per square inch, 20,000,000 pounds per square inch, and 12,000,000 pounds per square inch, for the three classes of iron, while at 20,000 pounds per square inch stress the value of E has dropped to about 25,000,000 pounds per square inch, 16,000,000 pounds per square inch, and 8,000,000 pounds per square inch, respectively.

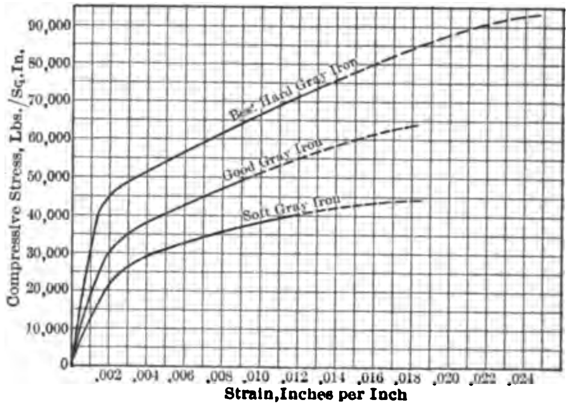

FIG. 185.—Stress-strain Diagrams for Cast Irons. (Compression.)

373. Allowable Stress in Compression. The safe working stress usually assumed for cast iron in compression is about 16,000 pounds per square inch for short blocks. For columns or other structural members in compression this value may be reduced 50 per cent or more, depending upon the ratio of length to radius of gyration of the section. The factor of safety employed is, therefore, not more than about four in most cases.

CROSS-BREAKING STRENGTH

374. Cross-breaking Strength, Modulus of Rupture. The cross-breaking strength of cast iron is coming to be almost universally depended upon as the criterion by which the quality of the material going into gray iron castings is to be judged. Cross-breaking strength is closely allied to tensile strength, since bending stresses are a combination of tensile stresses below the neutral axis of the beam with compressive stresses above the neutral axis. The extreme fiber stress on the tension side of the beam is naturally the controlling factor, since cast iron is so much stronger in compression than in tension, and the load which produces failure is that load which causes an extreme fiber tensile stress equal to the ultimate tensile strength of the material.

The cross-breaking strength is commonly expressed by use of the term "modulus of rupture," meaning the extreme fiber stress under the load which produces rupture as computed from the rule,

$$f = My_1 \div I,$$

wherein f is the extreme fiber stress, M is the bending moment, y_1 is the distance from the neutral axis to the extreme fiber, and I is the moment of inertia of the section.

As a matter of mechanics, this procedure is a wholly unwarranted one, since it involves the assumption that the neutral axis remains a constant distance from the extreme fiber, and the further assumption that a constant proportionality of strain to stress obtains for all stresses up to the breaking stress, i.e., it is really assuming that the stress-strain curve for cast iron is a straight line throughout.

We have seen, however, that the proportion of strain to stress is not a constant for any range of stress, and it is a well-understood fact that the neutral axis shifts upward as the material deforms. Therefore the actual extreme fiber stress is far less than the value of f computed by the rule for the bending moment which exists under the load which produces rupture, and, indeed, the actual fiber stress is in the case of cast iron not more than 50 to 60 per cent of the modulus of rupture.

For rectangular sections the above rule reduces to the form

$$f = 3Wl \div 2bh^2,$$

the specimen being simply supported on a span l and broken by a central concentrated load W (b is the width of the specimen and h is the height). The corresponding form of the rule for a circular section is –

$$f = Wl \div 2\pi r^3.$$

The factors influencing cross-breaking strength are of course exactly the same factors as those discussed in their bearing upon tensile strength, since failure under transverse loading is really failure by tension on the under side of the beam.

In addition to these factors which have been discussed above, however, it has been clearly shown that the transverse strength of cast iron is also dependent in some degree upon the size and shape of the specimens and the span upon which they are supported under load. Many series of tests, notably those of Mr. W. J. Keep,* have shown that specimens of small sections show relatively very much higher transverse strength than do specimens of large section, and are also much more sensitive to small variations in composition. Other tests have shown conclusively that rectangular specimens cast horizontally show a much higher transverse strength than do round specimens cast vertically.

In view of these circumstances efforts have been made by the American Society for Testing Materials to determine the size and shape of test specimen best fitted for adoption as a standard, and also the proper span upon which the beam should be supported. Their investigations have led to the widespread adoption of the "arbitration test bar" which is circular in section, $1\frac{1}{4}$ inches in diameter, and 15 inches long. The bar is broken under a central load upon a span of 12 inches. The propriety of maintaining the present standard 12-inch span in testing the arbitration bar has been seriously questioned. The point involved is well shown by the series of tests of arbitration bars made by Mr. C. D. Mathews † which are represented by the diagrams of Fig. 186. In these diagrams breaking strength is expressed by the modulus of rupture. The average given represents 10 tests of the same iron except in the cases of the bars broken on a 12-inch span and those broken on a 24-inch span, in which cases nine tests were made.

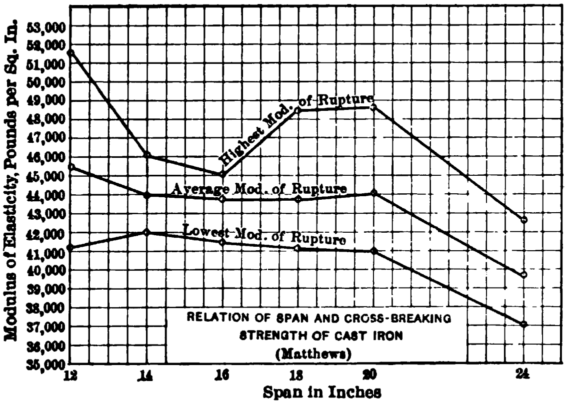

FIG. 186.

From the character of the results attained in these tests it would seem desirable to increase the standard span for testing arbitration bars

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* W. J. Keep, loc. cit. p. 120.

† Proc. Am. Soc. Test. Matrls., Vol. X, p. 304.

to 14 or 16 inches, either of which spans would seem to give more uniform results than are obtained with the present standard span or with longer spans than 16 inches. These tests are not sufficiently extensive to justify any change, however, unless their results are corroborated by further investigations.

375. Specification and Allowable Cross-bending Stress. The American Society for Testing Materials specifies that the minimum breaking strength of the arbitration bar under transverse load (the load being applied centrally on a span of 12 inches) shall not be under:

2500 pounds for light castings;
2900 pounds for medium castings;
3300 pounds for heavy castings.

Also, " the deflection shall in no case be under 0.10 inch."

These loads on a span of 12 inches correspond to the following values of the modulus of rupture:

39,000 pounds per square inch for light castings;
45,000 pounds per square inch for medium castings;
52,000 pounds per square inch for heavy castings.

The specified minimum deflection of 0.10 inch is designed as a measure of the shock resistance of the material. It is a common practice to assume that the " modulus of shock-resistance " of cast iron is expressed by multiplying one-half the breaking load by the total deflection and dividing the product by the volume of the material of the specimen between the supports. The only error involved in this practice lies in the assumption that a constant ratio of load to deflection obtains up to the breaking load. This means that the load-deflection curve is assumed to be a straight line, so that the half-product of load and deflection will be the area of the load-deflection curve and therefore expresses the work done in deforming the beam. As a matter of fact, this curve is never a straight line, the ratio of load to deflection decreasing as the load increases. The modulus of shock resistance is, therefore, like the modulus of rupture, simply an expression which will indicate approximately the relative behavior of different cast irons under transverse load, and is not a concrete expression of actual strength or resistance to shock.

CHAPTER XIII

MALLEABLE CAST IRON.*

GENERAL

376. Definition of Malleable Cast Iron. Malleable cast iron is iron of special composition which, after having been cast in its final form, is rendered malleable by a process of annealing. It is essential that the iron used be a white iron before annealing, in order that the carbon may be almost wholly in the combined form. The annealing process will then result in the conversion of the combined carbon into free carbon in an amorphous condition, not resembling free carbon in the crystalline form as graphite. This amorphous carbon will exist as isolated particles in a continuous mesh of metal. The casting is through this circumstance rendered very much tougher than white or gray cast iron, and its ductility and malleability are increased to such an extent that it may be bent or twisted to a considerable degree even when cold.

377. Malleable Cast Iron as a Material of Engineering Construction. Malleable cast iron has no important applications as a purely structural material, but is largely used in the manufacture of machinery, implements, railway rolling stock, light hardware, etc.

It combines the advantages of ordinary cast iron with respect to the ease with which complicated forms may be cast, with a degree of toughness, ductility, and strength approaching that of steel. Only cast steel or steel forgings can compete with malleable iron for the class of uses above noted, and where either material might be used the malleable iron will usually possess an advantage in cost.

MANUFACTURE OF MALLEABLE CASTINGS

378. The Materials Used. The charge of the furnace of a malleable-iron foundry includes pig iron, sprues, annealed malleable-iron scrap,

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* Practically the only satisfactory modern treatments of this subject are the works of Richard Moldenke, "The Production of Malleable Castings," 1911, and "Malleable Castings," the latter published in three parts by the International Correspondence Schools.

and steel scrap. Wrought-iron scrap, cast-iron scrap, and ferro-silicon are also used in some cases.

The pig iron should contain not more than 0.60 per cent manganese, not more than 0.225 per cent phosphorus, and not more than 0.05 per cent sulphur; total carbon need not be specified. The silicon requirement varies according to the castings made. Heavy castings require from 0.75 to 1.50 per cent silicon, while light castings require from 1.26 to 2.00 per cent. Several irons of different silicon contents are usually kept on hand.

The sprues or " hard scrap " include the gates and scrap castings that have not been annealed. Thorough cleaning of the sprues in tumbling barrels to remove the burnt sand is very necessary. The proportion of sprues in the charge may run from 25 per cent to as much as 60 per cent.

Malleable scrap is difficult to melt because of the comparative infusibility of the skin of malleable castings. It contributes greatly to the strength of the castings made, however, and if the large scrap is broken up before charging, it may be handled without serious difficulty. The proportion of malleable scrap used depends upon the proportion of sprues, but should not generally exceed 20 per cent.

Steel scrap of any sort, providing only that it be not too heavy, may be used as a part of the charge with beneficial results, if added after the balance of the bath is molten. (Otherwise, it would become oxidized.) The addition of steel scrap affords a method of reducing total carbon and produces stronger castings. Steel scrap is not used for cupola melting, and is never allowed to amount to more than 10 per cent with no malleable scrap present.

Wrought-iron scrap is sometimes substituted for steel scrap or malleable scrap, a much lower proportion being used. About one-fifth as much wrought iron may be substituted for steel, or one-twentieth as much for malleable scrap.

Cast-iron scrap is only used incidentally in place of so much pig iron. The maximum allowance does not exceed 5 per cent.

Ferro-silicon is used only in emergencies to save a heat which has been improperly managed or burned, or, by additions in the ladle, to render iron intended for heavy castings suitable for light castings.

379. The Furnace. Three types of furnaces are principally used in melting iron for malleable casting: the cupola, the air furnace, and the open-hearth furnace. The cupola furnace has been fully described in Art. 331 and the air furnace in Art. 332. The open-hearth furnace used in the malleable-iron foundry differs in no essential respect from the open-hearth steel furnace, hereinafter described, except in size, the capacity of the open-hearth furnace used in the malleable-iron industry being usually from 10 to 20 tons only.

380. Melting Malleable-iron Mixtures. The cupola process for melting iron for malleable-iron castings differs in no respect from ordinary gray-iron foundry practice, described in Arts. 334 and 339, except in the higher proportion of fuel charged. The fuel charge amounts to about one-fourth the weight of the metal charge when the iron is of the composition required for malleable castings. The advantages of the cupola process lie in the cheapness of installation and operation, the comparative ease with which the furnace is controlled, and the small loss of silicon in melting. The disadvantages are the extreme liability of burning, owing to the direct contact of metal and fuel, and the extremely close structure of the hard castings produced, which causes trouble in annealing. Very little malleable scrap, and no steel, can be used in the cupola, because of the great danger of burning. Cupola iron requires an annealing temperature 100 to 150° C. higher than does iron melted in the air furnace or open-hearth.

The operation of the air furnace has been fully discussed in Arts. 340 to 342. The advantages of the air furnace as compared with the cupola are principally the better grade of castings produced, the wider range of scrap material used, the shorter time required for pouring, the less serious consequences of a breakdown, and the better control over process and product. The disadvantages of the air-furnace process are the greater expense of equipment, the greater skill required in operation, and the longer time required in melting. A few years ago the air furnace was rapidly replacing the cupola in malleable-iron foundries, and it still remains the most important type of furnace used in this country. At the present time, however, the general preference is for the open-hearth furnace.

The open-hearth furnace is operated in the malleable-iron foundry in almost exactly the same manner as in the production of open-hearth steel, described in a later chapter. Its advantages over the air furnace are the saving of time (about one hour) required for melting, the very exact control of the process, and the resultant high efficiency and gain in the percentage of first-grade castings. The disadvantages are the high cost of installation, the heavy repair bill, the necessity of having gas fuel—meaning the installation of a gas producer if natural gas is not available—and the necessity of continuous operation.

381. Molding Methods for Malleable Castings. Molds for malleable castings are made in exactly the manner above described for gray-iron castings made in green sand.

Particular care must be exercised to provide proper gating in handling white-iron mixtures, and risers or feeders must be provided where thin sections are encountered to prevent cooling of the metal at these points before the mold is completely filled, resulting, because of the excessive shrinkage, in the production of spongy spots.

Chills are very commonly used in molds for malleable castings, particularly for the sake of cooling the larger parts of castings rapidly, thereby preventing the possibility of graphite separating out, as it tends to do with slow cooling.

382. Pouring the Castings. Molten white iron is a very different material from molten gray iron. The former must be poured very hot, and as rapidly as possible, to insure proper complete filling of the mold. White iron at a scintillating white heat is not as hot as gray iron at a bright red heat, the melting-point of white iron being more than 100° C. below that of gray iron. Iron which has chilled slightly, or which has been burned in the furnace, will be sluggish, and must not be poured except in pig-beds for use in subsequent heats.

383. Subsequent Treatment of the Castings. Hard castings for malleable iron are cleaned by any of the methods common to the gray-iron foundry. Tumbling is very commonly resorted to, and the sand blast, or pickling in acid solutions are not infrequently used.

Very careful inspection of the cleaned castings is necessary, and all defective castings are rejected before being annealed. The gates are also chipped off and the castings are separated into a number of classes for annealing.

384. The Annealing Process. The annealing process consists in heating the castings to a red heat and maintaining them at that temperature for a sufficient time to change practically all of the carbon from the combined form to the free amorphous form called "temper" carbon. In order to prevent oxidation at this temperature, and also warping of the castings, the latter must be packed in annealing pots surrounded by a proper packing material.

This packing material might be sand, clay, or other inert material and the heat alone would effect the desired change in the state of the carbon and produce malleable castings. Higher grade and stronger castings are produced, however, when the packing material is a decarbonizing agent such as iron oxide. This results in the migration of carbon from the outer shell of the casting, producing a layer resembling steel about $\frac{1}{16}$ inch thick, encased in a skin of almost carbonless iron on the surface. This skin may subsequently be enriched in carbon by a case-hardening process, and if the reduction of carbon has previously been carried to the maximum depth possible (about $\frac{1}{4}$ inch), the resultant material will greatly resemble cast steel. It may even be hardened and tempered.

The annealing pots are usually three or four cast-iron boxes, without bottoms, stacked one above another, and placed on a "stool" which supports them above the floor of the furnace. The usual size of the annealing pots does not exceed 18 by 24 inches, 15 inches high, but pots of specially large size or of special form are sometimes required.

The packing material used is commonly the cinder or slag squeezed from the wrought-iron puddle balls. This slag is a very rich iron oxide high in silica. Hematite ore in a pulverized state is also used as a packing material, especially for cupola iron whose annealing temperature is sufficient to cause puddle cinder to cake together and fuse onto the castings. Rolling-mill scale is also used, and magnetite has recently been found very satisfactory. If sand has not been perfectly removed from the castings, it causes trouble by combining with the oxide of the packing material, increasing its fusibility and causing the castings and packing to bake together.

The annealing oven or furnace is built in many quite different forms, the principal factors being the type of fuel used and the mechanical equipment of the plant. In general, the oven usually utilizes the down-draft principle and, since the castings must cool slowly in the furnace itself, it cannot be continuous in operation, and does not employ the regenerative principle. Fig. 187 illustrates one common type of annealing oven employing natural-gas fuel. The flames are deflected downward from a vaulted roof, pass between the pots, and escape through floor openings to flues beneath leading to the stack. A damper in the stack flue is depended upon to control the draft. Large ovens are provided with gas burners at either end.

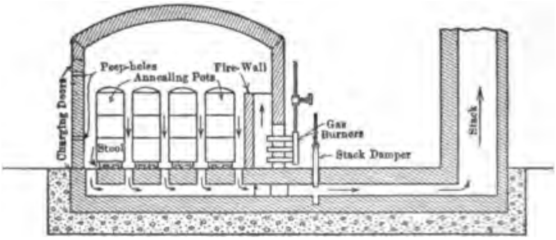

Fig. 187.—Annealing Oven for Malleable Cast Iron.

Producer gas may be used in exactly the same way except that, owing to its lower calorific value, it must be burned in greater quantities. When coal fuel is used the gas burners are replaced by grates, a firing door, and an ash pit.

Ovens are usually built in batteries of from six to twelve, adjacent ovens having common side walls. When overhead cranes are used for charging and discharging, the roof arches may be built in such a way that they may be removed in sections by the charging crane.

Two standard annealing processes are in use, depending upon the class of malleable produced. " Black-heart " malleable is usually produced in American practice, while " white-heart " malleable is usually produced in European foundries. The latter process requires a higher annealing temperature, which is maintained for a much longer time.

Most annealing ovens will attain the required temperature of 700° to 750° C. (800° to 900° C. for cupola iron) in from 24 to 36 hours; some ovens, however, require from 48 to 60 hours in heating up. The annealing temperature is maintained for a period of about 60 hours in the case of black-heart castings, and 100 or even 120 hours for white-heart castings. In the black-heart process but little of the temper carbon is removed, as is shown by the fracture, wherein only a very narrow band of gray material encloses the velvety black interior. The white-heart process is seldom applied to metal more than $\frac{1}{2}$ inch thick, and the removal of carbon is carried to the ultimate degree possible, the decarburization being effected to a depth of as much as $\frac{3}{16}$ or even $\frac{1}{4}$ inch.

The cooling of the castings after annealing should be as slow as possible. Usually from fifty to sixty hours are permitted before the pots are withdrawn from the oven. The entire annealing process therefore requires, as a rule, about six days. This period may be shortened to about four days, but not with best results.

385. Treatment of Annealed Castings. The annealed castings must be cleaned to remove the scale which has formed. This is accomplished in tumbling barrels, the only abrasive used being small pieces of annealed scrap. For delicate castings, or when a polish is desired, a part of the scrap may be replaced by wooden blocks, leather, etc.

In order to test the quality of the annealed iron, "test-plugs," which are simply small projections, about $\frac{3}{4}$ by $\frac{1}{2}$ by 1 inch long, are cast on the more important work. These are broken off and the fracture examined. If normal, the fracture should have a black velvety surface in the interior, surrounded by a band of dark gray about $\frac{1}{16}$ inch thick, and this in turn is encased in a band of white not more than $\frac{1}{64}$ inch thick. Too low silicon increases the width of this band.

PROPERTIES AND USES OF MALLEABLE CASTINGS

386. Chemical Composition and Constitution. The proper composition of good malleable iron is indicated by the following analysis:

Silicon	0.45–1.00%
Manganese	about 0.30
Phosphorus	not more than 0.225
Sulphur	not more than 0.06
Total carbon (before annealing)	at least 2.75

The constitution of malleable iron is extremely variable, even in a single casting, because the effect of the annealing process is largely dependent upon the thickness of the casting. The outermost skin is practically carbonless iron, and will therefore consist largely of ferrite together with a very small proportion of impurities which were originally present in the metal. The intermediate gray portion of black-heart malleable consists largely of ferrite, but contains scattered particles of free carbon in the amorphous state called temper carbon. The black interior consists of ferrite in which many isolated particles of temper carbon are interspersed. White-heart malleable castings have the constitution of the intermediate portion of black-heart castings for the most part, but the outermost band of practically pure ferrite is much thicker in the case of the former than in the case of the latter.

387. Physical Properties. Tensile Strength and Ductility. The tensile strength of malleable castings is much more important than the tensile strength of ordinary gray-iron castings, and the tensile test is a better indication of the quality of malleable iron, because the ductility of the material allows it to be evenly gripped in the jaws of the testing machine without danger of introduction of cross-bending stresses.

Tensile tests of malleable iron are commonly made on 1-inch square bars, 14 inches long, especially cast without the use of chills. Elongation is measured over a 2-inch gauged length, the fracture being included in this length. The average strength of black-heart malleable castings is usually not less than 40,000 pounds per square inch and sometimes exceeds 50,000 pounds per square inch. The elongation in 2 inches is seldom less than 2½ per cent, and may amount to as much as 7 per cent.

388. Transverse Strength. The transverse test of malleable iron is important because it is an indication of ductility and toughness as well as transverse strength. The transverse strength is determined by supporting a 1-inch square bar on a span of 12 inches and applying a central concentrated load. Observations of deflection under the breaking load are made. The usual breaking load for such specimens is not less than 3000 pounds, with a deflection of ½ inch and for specially well-made malleable castings the breaking load may amount to as much as 5000 pounds, with a deflection of 1½ inches. (The above loads correspond to moduli of rupture of 54,000 pounds per square inch, and 90,000 pounds per square inch, respectively.)

389. Toughness or Shock Resistance. Impact tests, unfortunately, have not been standardized for malleable cast iron, and no quantitative data concerning its shock resistance are available. An approximate measure of its toughness is obtained, however, from the observed deflection in the transverse test, the so-called modulus of shock resistance or resilience being computed (as in the case of tests of gray-iron arbitration bars) by dividing one-half the product of breaking load and total deflection by the volume of the specimen between the supports.

The very excellent performance of malleable iron under shock is well understood, however, and it has long been considered to be especially adapted to use where oft-repeated light shocks are encountered. For this class of service it is often considered superior to cast steel.

390. Uses of Malleable Castings. The uses for which malleable castings are especially adapted are very numerous. As above noted, this material is especially useful in the manufacture of that large class of articles whose form is too complicated for economical forging, but which must possess a strength and toughness not attainable in gray castings.

Among the more common applications of malleable iron may be especially mentioned its use on railroad work. Couplers are commonly made of malleable iron, as are the journal boxes, brake fittings, and many other small fittings for rolling stock. Other uses include many agricultural implements and parts of agricultural machinery, all manner of pipe fittings, elbows, unions, valves, etc., and all kinds of household and harness hardware such as parts of locks, hinges, window and door fittings, buckles, swivels, etc.

Another class of articles are made of malleable iron which has been case-hardened after prolonged annealing. The material then closely resembles cast steel, and is often sold as such. This class of articles includes many carpenter tools, such as hammers, hatchets, chisels, planer irons, etc., also pistol parts, skates, shears, etc.

CHAPTER XIV

WROUGHT IRON

GENERAL

391. Historical. The history of the development of the art of the iron maker, and the use of iron in the making of implements, machines, and structures, is almost a chronicle of the advance of civilization. Since the earliest ages iron has been the one metal of greatest value to man, and when or where the first discoveries of its virtues were made are facts which are shrouded in the mists of antiquity.

Antiquarians have found evidence which seems to show that the Egyptians, whose civilization is the oldest of which we have any accurate knowledge, possessed "bars of wrought metal, and vessels of copper, and of bronze, and of iron" * seventeen centuries before the beginning of the Christian era. Iron was known to the Carthaginians probably one thousand years before Christ, and was also employed by the Chaldeans, the Babylonians, and the Assyrians, who were contemporaries of the early Egyptians. Old Testament History is replete with references to the use of iron in implements of both peace and war.

Herodotus, writing in the fifth century before Christ, speaks of "the Chalybians, a people of iron workers," and also mentions the use of both iron and steel by the Persians, the Medes, and the Parthians. Irons and steels are known to have been made in India probably a thousand years before Christ, and the famous swords of the city of Damascus, the "Damascus blades" of song and story, were made ages ago from Indian and Persian steel.

The primitive methods of derivation of iron from ores were all direct methods, as has been above explained, and the irons produced in the charcoal fire and the Catalan forge and other types of ore refineries developed at a somewhat later date, were for the most part essentially what we call "wrought iron" to-day. Steel was similarly made at almost as early a period, but only under especially favorable conditions obtaining in certain districts, and its production was never so common among

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* From inscription found at Karnak.

ancient peoples as was the production of wrought iron. (Primitive methods of iron refinement roughly resembling the modern crucible steel process are believed to have been used in the production of the ancient Indian and Persian steels.)

Charcoal bloomeries and Catalan forges, not extensively modified or improved upon, were the only source of iron for many centuries. Furnaces which were able to render molten iron from the ores, by utilization of tall vertical shafts and stronger blast pressures (the first true blast furnaces), were developed in Belgium during the fourteenth century, and the first method of production of wrought iron from pig iron, in what was essentially a puddling furnace, was developed in England 400 years later, mainly by Henry Cort, whose patent for producing iron by the puddling process was obtained in 1784.

From the time of Cort the development of the wrought-iron industry was very rapid until the invention of the Bessemer steel process in 1855. It was confidently predicted at that time that the availability of cheap Bessemer steel would speedily put an end to the production of wrought iron, by crowding it from every field which had theretofore been peculiarly its own. This prediction has not been fulfilled, however, although wrought iron has been crowded from many fields, and has fallen far behind steels in the importance of its industry and in rank among materials of engineering construction.

392. Definition of Wrought Iron. The term "wrought iron" is commonly applied to that commercial form of iron which is obtained by the refining of a mixture of pig iron and scrap iron at a temperature not sufficient to maintain the metal in a molten state after the removal of its impurities, but only in pasty condition, the iron being intermixed with a considerable amount of the slag formed in the process.

The Committee on Uniform Nomenclature of Iron and Steel of the International Association for Testing Materials defines wrought iron as "malleable iron which is aggregated from pasty particles without subsequent fusion, and containing so little carbon that it does not harden usefully when cooled suddenly."

English writers often employ the term "malleable iron" meaning "wrought iron" as above defined.

393. Wrought Iron as a Material of Engineering Construction. Sixty years ago wrought iron was the most important metallic material for general structural and construction purposes. It was rolled in all manner of shapes, and was used for frames of buildings, for bridges, ships, tanks, and structures of all kinds. Tools and implements were made of wrought iron whenever a hardened edge or surface was not required. Its uses in machine construction were legion, its strength, toughness, ductility, and forgeability making it available for many purposes which could not be served by cast iron, but which did not justify the use of the relatively expensive steel then available.

The introduction and rapid decrease in cost of Bessemer and open-hearth steel in the latter part of the nineteenth century gradually forced the abandonment of the use of wrought iron as a structural material for the frames of buildings, bridges, etc., and various steels are now preferred for many special construction purposes, for most tools, implements, machine parts, etc. Nevertheless, wrought iron still possesses an important place among materials of construction, and bids fair to continue so to do indefinitely. Its principal present uses are as a material for general forging operations, particularly where welding is involved, as rolled rods and bars, as wire, as welded pipe, and as a metal for roofs and sides of buildings and for tanks, etc.

THE MANUFACTURE OF WROUGHT IRON

The Wet-puddling Process

394. The Puddling Process in General. The usual process of manufacture of wrought iron consists in the melting of the pig iron in the hearth of a reverberatory furnace which is lined with iron oxides, resulting in the elimination of most of the carbon, silicon, magnanese, phosphorus, and sulphur present in the charge, by oxidation. The metal becomes pasty toward the end of the process, owing to the decreased fusibility of the purer iron, and is removed as a plastic ball from which the slag must be removed as completely as possible by squeezing or hammering. The resultant " puddled bloom " is rolled into large bars called " muck bars." The bars are cut into short lengths, piled up in bundles which are wired together, heated to a white heat, and rolled down to a smaller size called " merchant bars."

This process results in the production of the purest of the common iron products, if we disregard the presence of from 1 to 3 per cent of slag, which the rolling process has caused to assume the form of greatly elongated particles in the direction of rolling. This circumstance accounts for the characteristic fibrous structure of wrought iron, and the purity of the metal accounts for its remarkable ductility and weldability.

395. The Iron Used. The pig iron commonly used for puddling is a rather inferior grade called " forge-pig." Its composition is from 1.00 to 1.50 per cent silicon, 0.25 to 1.25 per cent manganese, not more than 1.00 per cent phosphorus, and not more than 0.10 per cent sulphur. Comparatively high silicon is desired in order to provide sufficient slag to cover the bath of metal and prevent excessive oxidation of the iron.

Manganese need not be carefully watched, because it is largely removed in the process. Phosphorus, and particularly sulphur, are not completely removed, and must therefore be kept fairly low, although their injurious effect upon the quality of the iron is by no means as marked as in the case of steel.

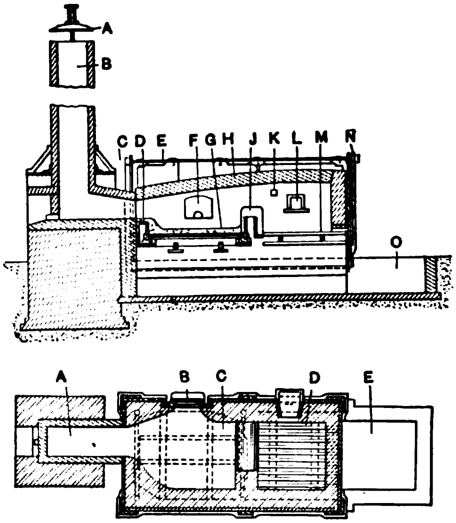

Fig. 188.—500-lb. Puddling Furnace. (Macfarlane.)

The weight of the furnace charge varies according to the size and type of furnace used. Ordinary single furnaces handle from 200 to 600 pounds of pig, while large furnaces, or double furnaces built in pairs without a dividing wall, may handle as much as 1500 pounds per charge. Charging is usually done by hand, the pig iron being thrown in through the firing door.

396. The Puddling Furnace. The puddling furnace is a rectangular masonry structure lined with firebrick and tied together by steel tie-rods and iron plates and buckstays. Fig. 188 illustrates a common type of puddling furnace of 500 pounds' capacity, worked from one side, and Fig. 189 illustrates a 1500-pound furnace with two work-doors. The furnace is of the reverberatory type, the heat depended upon to bring the working chamber to the desired temperature being largely that which is reflected from the sloping firebrick roof of the melting chamber, the fuel being burned in a separate chamber out of contact with the metal. Iron castings support the working bed of the furnace at a convenient height above the floor, thus permitting the free circulation of air beneath. A hollow cast-iron "fire-bridge" separates the firebox from the working chamber. It is protected from the flames sweeping across into the working chamber by a covering

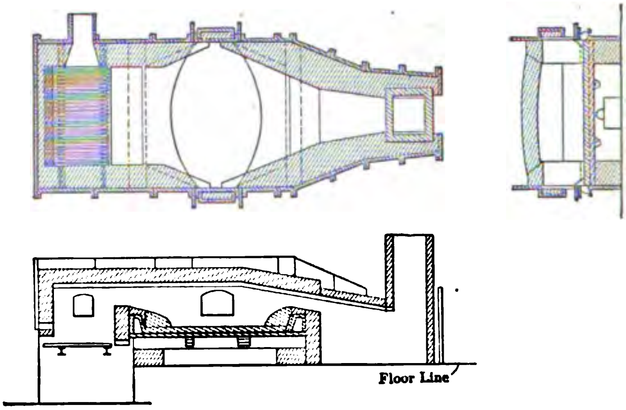

Fig. 189.—1500-lb. Puddling Furnace.

of refractory bricks or blocks, and is cooled by air driven through its hollow interior. The "flue-bridge" over which the waste gases pass from the working chamber to the stack is of similar construction. It is customary to arrange two or four furnaces to be worked by one stack, the flues from the individual furnaces being provided with dampers. Furnaces are not infrequently built in pairs back to back.

The area of the fire grate is large, usually about one-third of the area of the working part. The grate bars are usually of wrought iron and are easily replaceable. A steam injector is sometimes provided to supply extra air for the combustion of the fuel and to assist in the oxidation of impurities in the metal.

The fuel is a bituminous coal which burns with a long flame. It is introduced through a "firing hole" in the front wall. This hole, not being provided with a door, is usually partially stopped by lumps of coal. The large "working door" in the front wall of the working chamber has a heavy iron projecting sill and is normally closed by an iron-bound slab of brickwork which is suspended in place and balanced by a counterweight. A small opening in the lower edge of this slab affords an opportunity for the puddler to insert his "rabbling iron" to stir or "rabble" the charge. The slag is tapped off when necessary through a tap-hole provided below the working door.

397. Preparation of Furnace for Charging. The Fettling. The furnace hearth is lined, or "fettled," with strong iron oxides of basic character. The fettling requires extensive renewals after practically every melt.

The principal "fettling" materials used are: Basic slag from reheating furnaces; slag from the puddling furnace itself, usually roasted, but sometimes allowed to remain in the furnace from the previous melt; hammer scale, or roll scale, from the finishing mill, and hematite ore.

Sufficient fettling is usually employed to cover the iron plates to a depth of about 5 inches. The character of the fettling is variable, depending upon the character of the pig iron used. Easily fusible iron, i.e., very impure iron, requires a fusible fettling, and comparatively pure iron, which is therefore less fusible, requires a fettling which is less easily fused and less rich in oxides.

398. Furnace Operation. Chemical and Physical Changes. The furnace having been charged and a melting temperature attained, the subsequent process may be considered in four stages which merge into one another.

(1) The "Melting-down Stage." The pig iron gradually becomes red hot and is turned about by the puddler to insure uniform heating. The more fusible slag begins to melt within twenty minutes, and in the course of thirty to thirty-five minutes the pig iron will have become completely melted down. During this stage the oxidation of the metalloids will begin. The first to be oxidized is the silicon, followed by the manganese, and later by the phosphorus and sulphur. The oxides naturally leave the metal and join the slag in accordance with the fundamental metallurgical principles above stated. During this stage most of the

silicon and manganese are thus eliminated, together with a small proportion of the phosphorus and a very small proportion of sulphur.

(2) The "Clearing Stage." During this stage, which occupies only from seven to ten minutes, it is usually necessary to add ore or mill scale, thus making the slag still more basic, and to close the dampers to cool the furnace sufficiently so that the carbon will not be oxidized before the phosphorus and sulphur have been disposed of. Very vigorous rabbling is necessary to promote oxidation by intimate contact between the pig iron and the fettling. During this stage the removal of silicon and manganese is almost completed, so far as it ever will be, and a considerable further amount of phosphorus and sulphur is eliminated.

(3) The "Boiling Stage." This stage is principally characterized by the removal of carbon, through the agency of the fettling first, and later by the oxygen of the air. The ferric oxide is reduced by the carbon with the formation of carbon monoxide gas which bubbles to the surface, causing the boiling appearance characteristic of this period. It is especially essential that the slag be very strongly basic at this time, as it will otherwise be unable to retain the oxides of phosphorus and sulphur which the carbon monoxide might so easily reduce.

The carbon monoxide is burned by the oxygen of the air to form carbon dioxide, resulting in the appearance of the light yellow flames at the surface of the bath called "puddler's candles." The expansion of the bath during the boil causes its level in the hearth to rise greatly and a considerable amount of slag escapes through the open slag hole.

During the boil the puddler continues to rabble the mass vigorously, and after about twenty minutes the metal begins to "come to nature," i.e., non-fluid iron begins to collect in patches in the bath and on the surface in a pasty condition, owing to its lesser fusibility in its now nearly carbonless condition. Great care is required upon the part of the puddler to prevent this pasty iron becoming chilled by sticking to the hearth, or oxidized by exposure above the slag. At the end of from twenty to thirty minutes all of the metal will have come to nature and the removal of carbon will have reached its limit. A considerable further quantity of phosphorus and sulphur will have been eliminated during this stage (20 to 30 per cent of the phosphorus and sulphur is never removed.)

(4) The "Balling Stage." When all the metal has come to nature the balling stage begins. The puddler carefully gathers all of the pasty metal into one mass, which he subsequently subdivides into portions of such size as he is able to withdraw from the furnace. Each portion is worked into a ball and welded together as completely as possible. The balls are rolled up under the protection of the fire-bridge to prevent excessive oxidation of the iron before being withdrawn. The balls are

finally gripped with tongs, one by one, and drawn out of the door over the fore-plate to a conveyance which takes them to the squeezers as quickly as possible. The usual weight of these "puddle balls" is about 100 pounds, but is sometimes as much as 200 pounds.

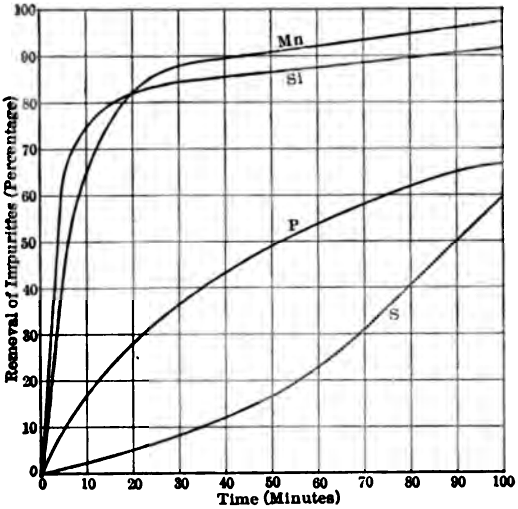

FIG. 190.—Sequence of Removal of Metalloids in Puddling. (Stoughton.)

The balling stage requires about twenty minutes altogether. It is characterized by no chemical changes, but the furnace temperature must be maintained as high as possible in order that the puddle balls may be hot enough so that the slag is still very fluid when they reach the squeezer. Fig. 190 shows graphically the approximate sequence of the removals of the metalloids during the operation of puddling.

399. Removal of Slag. Squeezing or Shingling. The puddle ball when removed from the furnace is a very loosely agglomerated mass of pasty iron, honeycombed with pockets of slag. This slag must be excluded, so far as is possible by mechanical means, and the iron compacted and welded together by one of the operations known as "squeezing," and "shingling," respectively.

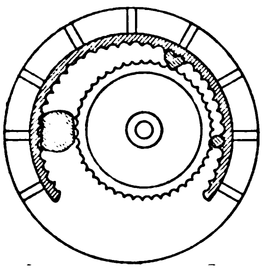

FIG. 191.—Rotary Squeezer.

In American practice some form of squeezer is practically invariably used. A very common type of squeezer is that shown in Fig. 191. A wheel mounted on a vertical axis revolves within an encircling cylinder of cycloidal form. Both wheel and cylinder have corrugated surfaces. The puddle ball is introduced at the point where the space between the two surfaces is a maximum, and the rotation of the inner wheel causes the ball to roll as it is carried around the annular space which is constantly decreasing in width. When the ball is finally ejected a large part of the slag will have been excluded and it will have been compacted by the kneading and squeezing to less than half its original diameter.

In European countries the puddle ball is usually "shingled," i.e., it is forged down by some type of power hammer. The steam hammer is now usually employed in shingling. Between blows the puddle ball is constantly turned by the operator until it has been thoroughly welded together and the slag largely excluded.

The compression of the porous mass of metal either in squeezing or shingling results in a considerable rise in temperature of the mass, which circumstance favors the expulsion of the slag by retaining it in a very fluid condition.

400. Rolling Mill Operations. The puddled "blooms" from the squeezer or the shingling mill are immediately transferred to the rolling mill wherein the finished bar or shape is produced. The bloom is first passed through a bar mill which reduces it to rectangular bars called "muck bars" which are 2 to 4 inches thick. These muck bars are then cut into strips which are piled up (Fig. 192), tied with wire, reheated to a welding heat, and again rolled down to form "merchant bars." A further quantity of slag is squeezed out in rolling. Usually the bars in a pile are all laid the same way, but occasionally they are "cross-piled," i.e., alternate layers are laid crosswise. This practice results in the production of a cross-network of fibers, instead of having all the fibers running lengthwise of the bar.

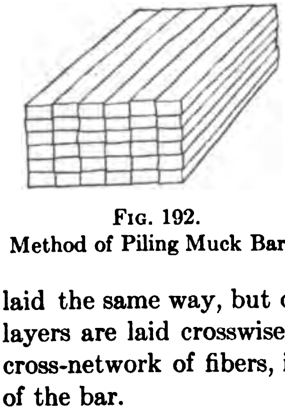
FIG. 192.
Method of Piling Muck Bars.

Bars which have been piled and rerolled are commonly called merchant bar or "single-refined iron"; when subjected to a second piling, heating, and rerolling, "double-refined bar" is produced. The effect of repeated rerolling is principally the further elongation of the strands of slag in the direction of rolling, thereby rendering the iron still more fibrous in its structure. No advantage is gained by piling and rolling more than about three times.

The final rolling is usually done in a mill called a "merchant bar mill," Fig. 193. A series of passes through the rolls serves to gradually reduce the bar to the desired size and shape. Roughing rolls are shown at *B* and *D*, Fig. 193, while finishing rolls for ovals and rounds are shown at *F* and *H*.

401. Mechanical Puddling. Efforts to avoid the very severe manual labor involved in hand puddling, by the use of devices which mechanically rabble the charge, have characterized the history of the industry for many years. None of these efforts have met with marked success, however.

The best-known mechanical furnace is the Roe furnace, shown in Fig. 194. It is suspended upon trunnions and caused to oscillate 65 degrees in each direction. Oil fuel is used, the oil and air for combustion being introduced through the hollow trunnions. A stack is provided at either end. The oscillations of the furnace keep the bath and slag well mixed, thus avoiding hand rabbling. The entire charge of the furnace, weighing about 4000 pounds, is discharged in one ball from which the slag is squeezed in a large hydraulic squeezer of special design.

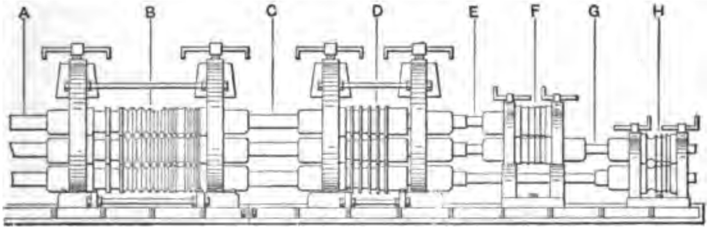

FIG. 193.—Merchant Bar Mill.

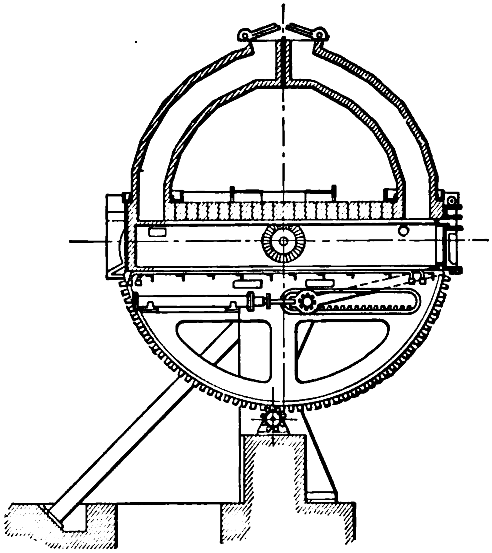

FIG. 194.—Roe Mechanical Puddling Furnace.

402. Wrought Iron from Scrap. A large proportion of the wrought iron made in this country is made, not by refining pig iron, but by heating and rolling scrap wrought iron.

Usually this scrap is simply bundled together and wired in a pile roughly resembling a pile of muck bars, heated to a welding heat, and rolled.

A second method of utilizing scrap is called "busheling scrap." Scrap iron of small size is gathered together, heated in a small furnace resembling a puddling furnace, and the product treated as an ordinary puddle ball.

A third method is called "fagoting," or "box piling." A rough box is made of muck bars which form the sides, bottom, and top, while the interior is filled with miscellaneous small scrap. This mass is wired together and handled just as a pile of muck bars would be handled.

All of the methods of making wrought iron from scrap without remelting result in the production of an inferior grade of material.

PROPERTIES AND USES OF WROUGHT IRON

403. Composition and Constitution. The composition of wrought iron approaches pure iron more closely than any other commercial form of iron. The usual impurities—carbon, silicon, phosphorus, sulphur, and manganese—are always present in small amounts, however, in addition to the slag which is invariably present. The following analyses are examples of the composition first, of an ordinary grade of wrought iron, and second, of a very pure Swedish charcoal iron:

Element	Ordinary Wrought iron %	Swedish Iron %
Total carbon	0.100	0.050
Silicon	0.200	0.015
Phosphorus	0.150	0.055
Sulphur	0.030	0.007
Manganese	0.010	0.006
Slag and rare elements	2.800	0.610
Iron (by difference)	96.710	99.257

The constitution of wrought iron is quite simple as compared with that of cast iron, because of the very low percentages of carbon and other impurities in the iron. The great bulk of the material is nearly pure ferrite (contaminated with small amounts of silicon, phosphorus, etc.), which consists structurally of crystalline grains of iron. The appearance of a longitudinal section of wrought iron under high magnification is shown in the photo-micrograph of Fig. 195. The presence of slag, appearing as many irregular black lines of varying thickness, is clearly evident. The crystalline nature of the ferrite is also plainly to be seen, thus refuting the belief which was long held that the peculiar properties of wrought iron were due to the fact that the minute structure of the iron was fibrous rather than crystalline as in steel. The micro-photograph of Fig. 196 shows the appearance of the transverse section of wrought iron. The structure is in every way similar to that revealed by the longitudinal section except that the slag here appears as irregular dark areas corresponding to the cross-section of the slag fibers.

A third constituent besides the ferrite and the slag is invariably recognized, owing to the fact that carbon is always present in some degree. This carbon will normally combine with the iron to form cementite, which latter unites with a definite portion of the ferrite to form pearlite. Since the carbon content is normally very low, the pearlite constituent is not conspicuous, but occurs only in isolated small patches between the grains of ferrite.

FIG. 195.—Wrought Iron. Longitudinal Section. Magnified 100 Diameters. (Boynton.)

The constitution of the slag itself is rather complex, being made up of silicates and phosphates of iron and manganese, formed by the combination of the acid and basic oxides which have joined the slag during the puddling process (the Fe_2O_3, FeO, MnO, SiO_2, P_2O_5, etc.).

404. Classes of Wrought Iron. Wrought irons may be classed according to method of manufacture, or according to the class of uses for which they are intended. The first classification comprises the following:

(1) *Charcoal iron* is that made by refining either the ordinary blast furnace product or the product of blast furnaces worked with charcoal fuel in a charcoal hearth. *Knobbled charcoal iron* is simply iron made in a special type of charcoal hearth after melting in a coke refinery. Charcoal irons are the purest grades of

FIG. 196.—Wrought Iron. Transverse Section. Magnification not Stated. (Guillet.)

wrought irons and are much used for conversion into cementation steel and crucible steel by a process of recarburization.

(2) *Puddled iron* is that made by the wet puddling process above described. Newly puddled iron is sometimes called *muck-bar iron*, or *puddled-bloom iron*, to distinguish it from scrap puddled-iron. *Box-piled iron* may be made entirely from puddled iron or may be made from muck-bar iron and scrap.

(3) *Busheled scrap* is a heterogeneous product made by heating and rolling busheled or fagoted scrap by the processes above described.

The principal classes of wrought iron according to the uses for which their qualities fit them are *staybolt iron*, *engine-bolt iron*, *refined-bar iron*, and *wrought-iron plate*.

Staybolt iron is made from puddled or knobbled charcoal iron. It is the highest grade of wrought iron and, while not the strongest, it is the toughest and most ductile iron, the best for forging and welding.

Engine-bolt iron is made from the same class of material as staybolt iron, which it slightly surpasses in strength. It is slightly less tough and ductile, however.

Refined-bar iron is made from a mixture of muck-bar iron and iron scrap. It is inferior to stay-bolt and engine-bolt irons in strength, toughness, ductility and forgeability.

Wrought-iron plate is made in two grades or classes: Class *A* is made wholly from puddled iron, and is a strong hard iron, but lacks ductility and toughness when compared with the best grades of iron. Class *B* is made from a mixture of puddled iron and scrap material, and is inferior to class *A* iron plate in every respect. Neither class of wrought-iron plate is intended for forging or welding.

405. Tensile Strength and Elongation. The tensile strength of a given wrought iron is dependent upon the direction of stress with respect to the " grain " of the iron. This is naturally to be expected, since, as we have seen, the continuity of the metal in a direction transverse to the direction of rolling is interrupted by numerous strands of slag which are structurally very weak. The tensile strength of wrought iron in a transverse direction has usually been found to be between 0.6 and 0.9 of the strength in a longitudinal direction. It will therefore be safe to assume, in the rare instances when we are concerned with the strength in a transverse direction, that this strength is about three-fourths the strength in the direction of rolling. When the muck bars have been " cross-piled " the strength in a transverse direction may practically equal the strength in the longitudinal direction.

The tensile properties of wrought iron in general are quite variable; but, when we recognize the several grades above listed, the properties of a given grade become quite definitely fixed. The specifications of the American Society for Testing Materials adopted in 1912 and 1913 prescribe the following tensile properties:

Property.	Staybolt Iron.	Engine-bolt Iron.	Refined Bar Iron.	Wrought-iron Plate.			
				6-24 Ins. Wide.		24-90 Ins. Wide.	
				A	*B*	*A*	*B*
Tensile strength, pounds per square inc..........	49-53,000	50-54,000	48,000	49,000	48,000	48,000	47,000
Yield point..............	0.6 (ten. str.)	0.6 (ten. str.)	25,000	26,000	26,000	26,000	26,000
Per cent elongation in 8 ins.	30	25	22	16	14	12	10
Per cent reduction of area.	48	40					

The "Modulus of Elasticity" of wrought iron varies little for all the different grades. It will usually be found to be between 26,500,000 pounds per square inch and 28,000,000 pounds per square inch.

A typical stress-strain curve for high-grade wrought iron is shown in Fig. 197.

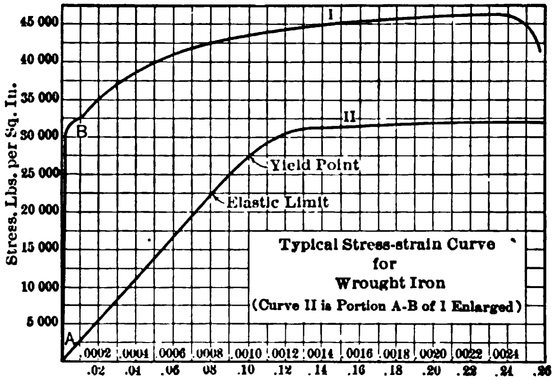

FIG. 197.—Typical Stress-strain Curve for High Grade Wrought Iron.

406. Relationship between Tensile Properties of Wrought Iron and Reduction in Rolling. A fairly definite relationship exists between the tensile properties of wrought iron and the amount of reduction in rolling. It is often asserted that the strength of wrought iron is inversely proportional to the cross-sectional area. It is probable, however, that this is true only in so far as the smaller sizes represent a greater percentage reduction in rolling from the original pile of muck bars. Extensive tests made by the U. S. Board on Testing Iron and Steel in 1881 show that practically the same tensile properties are shown by all sizes of wrought-iron rods provided only that the ratio of finished size of bar to size of pile be kept constant.

Fig. 198 has been plotted from the data obtained in the series of tests above mentioned. It will be noted that the relationship between tensile properties and reduction in rolling is by no means constant, but both ultimate tensile strength and elastic limit are raised considerably by decreasing the ratio of section of finished bar to section of pile. The effect is much more marked with respect to the elastic limit than with respect to the ultimate strength.

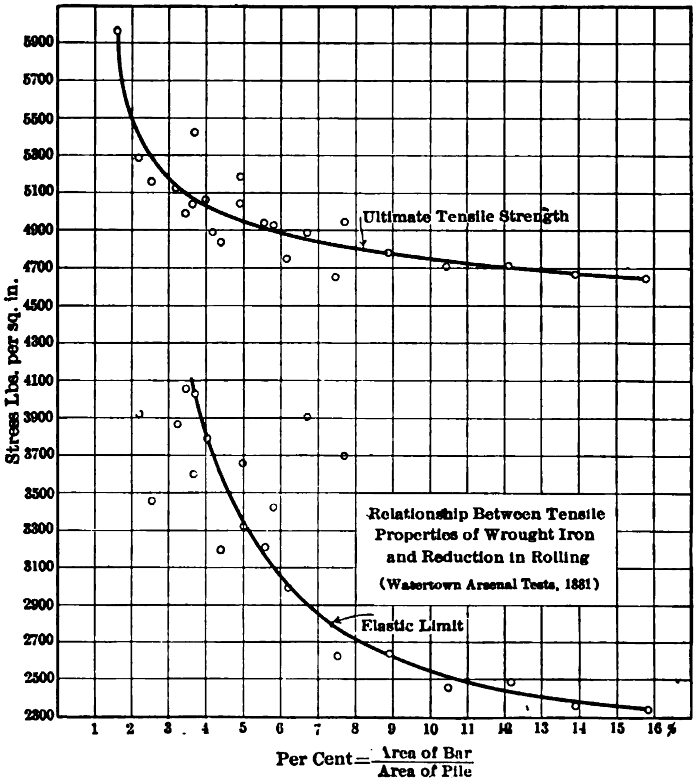

FIG. 198.—Relation Between Tensile Properties of Wrought Iron and Reduction in Rolling.

407. Effect of Previous Straining or Cold Working upon Tensile Properties. The effect of previous straining of wrought iron upon the elastic limit and ultimate strength revealed by subsequent test is greatly to raise the elastic limit and considerably increase the ultimate strength. The magnitude of the change effected will be dependent upon the extent to which the previous straining was carried beyond the elastic limit of the material in its original condition, and the maximum effect will be noted when the specimen is actually broken in the initial test and the subsequent test made upon the portion of the specimen immediately adjacent to the fracture.

The effect of previous straining upon the tensile properties of wrought iron as revealed by a subsequent test is shown forcibly by Fig. 199, wherein *I* is the stress-strain curve obtained in the original test of a wrought-iron bar,* and *II* the stress-strain curve derived in a subsequent test of the portion of the original bar adjoining the fracture.

The elastic limit of the bar upon retest has been increased from 30,000 pounds per square inch to 59,000 pounds per square inch, while the ultimate strength has been raised from 53,700 pounds per square inch to 64,000 pounds per square inch. The elongation after fracture has been reduced from 16 per cent in a 100-inch gauge length to 5.3 per cent in a 50-inch gauge length. (These elongations appear small because the gauge length is unusually large.) The modulus of elasticity is not changed in any degree by the previous straining.

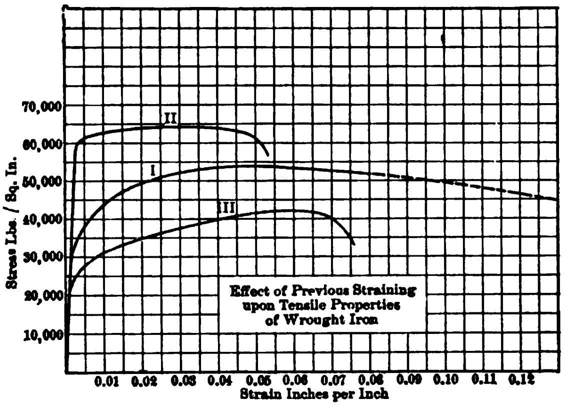

FIG. 199.—Effect of Previous Straining and Annealing upon Tensile Properties of Wrought Iron. (Wat. Ars. Tests, 1882.)

Curve III, Fig. 199 shows the effect of annealing upon the tensile properties of the previously strained bar. It will be noted that the effect of the former strain has not only been removed, but the elastic limit and ultimate strength have even been lowered below the values noted for the original bar. The explanation of this phenomenon will appear in the discussion which follows.

Cold working of wrought iron, i.e., deforming it by rolling, hammering, or pressing, at temperatures below about 680° C., affects the structure and the mechanical properties of iron in much the same way as straining it beyond the elastic limit in a test does. The elastic limit is considerably raised, the ultimate strength is slightly raised, and the elongation or ductility is usually lowered.

The beneficial effect of cold working is largely due to the fact that it

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* Watertown Arsenal Tests. 1882.

closes up the grain of the metal, and eliminates blow-holes. It also increases the cohesion and adhesion of the crystals, however, and if cold work follows hot work the size of the crystals will be decreased with consequent lessening of brittleness.

Of the several methods of cold working above mentioned, rolling is the most rapid and the cheapest, although it does not work the metal as well as hammering does. Pressing works the metal to a greater depth than either hammering or rolling and is especially necessary when the work is large. Hammering is commonly accomplished by the steam hammer, while pressing is done by hydraulic presses of from 500 to 1000 tons capacity.

408. Heat Treatment and Crystalline Structure. The size of the crystalline grains of ferrite in wrought iron is dependent—first, upon the temperature from which it cools; second, upon the length of time it is maintained at that temperature; third, upon the rate of cooling and the amount of mechanical work to which it is subjected during cooling; and fourth, upon the temperature at which working is discontinued.

In general, the higher the temperature, the larger the crystals will be, providing the time allowed at that temperature be not too short. Slow cooling also promotes crystalline growth, provided that the cooling be undisturbed. The application of pressure, however, either by rolls, hammer, or press, retards the formation and growth of crystals and breaks up or destroys pre-existing crystals. Thorough working to a temperature below the critical temperature above mentioned (about 690° C.), is necessary to overcome the injurious effects of the coarse crystallization which occurs at such high temperatures as are required, for instance, in welding.

409. Compressive Strength of Wrought Iron. The properties shown by wrought iron in compression do not differ materially from its tensile properties, i.e., its elastic limit, ultimate strength, and modulus of elasticity are about the same in compression as in tension, provided that the ratio of length to radius of gyration does not approach the point where lateral flexure occurs.. In the latter event the flow of the metal when the yield point is reached immediately causes eccentricity of stress, and ultimate failure ensues under an average stress which exceeds the yield point by very little or none at all.

The compressive strength of wrought iron may therefore be taken to be from 45,000 to 60,000 pounds per square inch if the length is very short in proportion to the radius of gyration. Usually, however, this proportion is too great to make it possible to disregard flexure, and the ultimate compressive strength must be taken to be only equal to the stress at the yield point, or from 25,000 pounds per square inch to 35,000 pounds per square inch, according to the character and condition of the iron.

All of the considerations above discussed with reference to the modification of tensile properties by variations in the amount of reduction in rolling, heat treatment, previous straining, etc., apply with equal force when we are concerned with compressive strength, except that we must not expect that previous straining in tension will improve the compressive properties revealed on subsequent tests. We find in fact that exactly the reverse is the case and that straining the material beyond its elastic limit in either tension or compression impairs its elastic properties under the opposite kind of stress.

410. Shearing Strength of Wrought Iron. Remembering what has been said above concerning the structure of wrought iron, it will at once be evident that the resistance of the material to shearing stresses will be far less on a plane parallel to the direction of the " grain " than on a plane which cuts the fiber of the iron transversely. It is a fact, indeed, that the shearing strength on a transverse plane is often twice that shown on a longitudinal plane.

The actual shearing strength shown by tests is very variable, but in general will be from 20,000 to 35,000 pounds per square inch on a longitudinal plane and from 30,000 to 45,000 pounds per square inch on a transverse plane.

411. The Welding of Wrought Iron. One of the most valuable attributes of wrought iron is the comparative ease with which it may be welded, i.e., the joining together of two pieces by simply pressing or hammering them together while at a very high temperature. Wrought iron possesses the property of weldability to a greater degree than any other metal except an equally pure low-carbon steel. Its superiority is due largely to its comparative purity, since all impurities, especially carbon, silicon, and sulphur, reduce weldability in a marked degree.

The exact temperature of welding is not known, but it is moderately close to the melting-point, probably between 1300° and 1400° C. At this temperature (a white heat) the metal becomes plastic, almost pasty, and remains so for a considerable range of temperature. In welding operations, however, two factors are operative which tend to prevent a perfect union, and the production of a joint as strong as the original metal. The first of these is the formation of iron oxide by the oxygen of the air; the second is the coarse crystallization which is always apt to occur at such high temperatures. (See Art. 408.)

Iron oxide forms very rapidly on iron at a welding heat, forming a coating of liquid slag which effectually prevents a proper union of the surfaces which are to be joined. The remedy lies in the removal of the iron oxide from the joint. This may be effected in large measure by simply making the two surfaces convex to each other. They then come in contact first at their centers, and as the area of contact spreads the slag is squeezed out. The exclusion of the slag is facilitated by the use of a flux which is a solvent for the slag and therefore renders it more liquid. Borax is commonly used for this purpose, and of late years " welding plates " (thin plates of flux which are inserted in the joint just before closing it) are sometimes used. Ordinary sand is a satisfactory flux in welding steel.

The effect of the rapid growth of the crystals at a welding heat is to produce a coarse-grained iron which lacks ductility and possesses great brittleness. The remedy lies in the refining of the metal by working it under the hammer or in a press until the critical range of temperatures has been passed. The danger due to coarse crystallization usually is not that the metal will be brittle just at the weld, for this portion will probably have been thoroughly refined by the working necessary to properly close the joint, but rather that the metal some few inches from the joint will have been overheated without subsequent heat refinement under the hammer. Such a joint may upon testing fail at a point somewhat removed from the weld itself, but this does not prove that the weld is stronger than the original bar.

The usual practice in welding consists in first " upsetting " the bars (enlarging the section, to provide extra metal for subsequent reduction in working, by endwise pressure or hammering of the two pieces) while at a forging heat, raising them to a white heat in a forge or otherwise, placing the pieces together on the anvil or block, adding the flux, and quickly closing the joint by hammering or by use of a press. Working is continued down to a red heat to effect a proper refinement of the crystals. It is desirable after cooling to reheat the parts to a point just above the critical temperature in order to restore the grain size.

The commonest types of welds are the " lap " or " scarf " weld, Fig. 200*a*; the " butt " or " jump " weld, Fig. 200*b*; and the " V-weld," Fig. 200*c*. The proper shape of the individual pieces for these welds are shown by Figs. 200*d*, 200*e*, and 200*f*, respectively.

Electric welding is an art quite distinct from ordinary hand welding. Here less difficulty is experienced in avoiding the injurious effect of oxidation, since no strongly oxidizing air blast is used, as in the case of the ordinary forge, and the pieces may be heated in direct contact with each other.

The temperature required may be attained electrically either by direct contact with—or by radiation from—an external electric arc; by making the joint itself the negative pole of an electric arc, the positive pole of which is a carbon rod; or by making the current traverse the pieces themselves, the increased resistance at the joint giving rise to the necessary welding temperature.

Owing to the possibility of great variations in the extent to which the above-mentioned factors may be operative, the strength of welded joints is extremely variable. Hand forging is usually less efficient than power forging and electric heating is more efficient than forge heating. In general the strength of hand-forged joints of average character is about 60 to 70 per cent of the strength of the bar. Power forging will raise the efficiency to from 70 to 90 per cent, and even higher efficiencies are sometimes attained by use of electric methods

Fig. 200a. Fig. 200d.

Lap or Scarf Weld.

Fig. 200b. Fig. 200e.

Butt or Jump Weld.

Fig. 200c. Fig. 200f.

Tongue or V Weld.

Fig. 200.—Various Types of Welds.

CHAPTER XV

STEEL

GENERAL

412. Definition. It is not possible to make a strict definition of steel which is concise and at the same time not in conflict with current usage. The term is applied to practically all the forms of iron produced either in the cementation furnace, the crucible, the converter, the open-hearth furnace, the electric furnace, a combination of the converter and the open-hearth, or a combination of either the converter or the open-hearth with the electric furnace. Still there are exceptions to the above statement which cannot be disregarded, among the most important of which is the use of the open-hearth in the production of malleable cast iron.

In the early days of the iron industry it was easy to distinguish between steel and cast iron by declaring all forms of iron which were malleable to be either steel or wrought iron; steel if it would harden upon sudden cooling, otherwise wrought iron. These distinctions will not hold at the present time, however, since many grades of steel are now made which will not harden upon sudden cooling; some are not malleable except through a certain range of very high temperatures; and one grade of iron, malleable cast iron, is malleable (after annealing) but cannot be classed as steel.

Professor H. M. Howe has proposed the following definition, which, although cumbersome, covers the ground adequately: " Steel is that form of iron which is malleable at least in some one range of temperature, and in addition is either (*a*) cast into an initially malleable mass; or (*b*) is capable of hardening greatly by sudden cooling; or (*c*) is both so cast and so capable of hardening."

The provision in the definition that steel " is malleable at least in some one range of temperature " distinguishes steel from cast iron and pig iron without excluding certain special steels like chrome and manganese steel, which are malleable only through a short range of high temperatures; the provision that it is " cast into an initially malleable mass " excludes malleable cast iron, which is rendered malleable by special treatment after being cast; and either the provision that it is " cast," or the provision that it " is capable of hardening greatly by sudden cooling " serves to differentiate it from wrought iron (which is never cast and is never capable of hardening), without excluding " cementation " or " blister " steel, which is not cast but will harden, or many low- or medium-carbon steels which are cast but will not harden.

The Committee on Uniform Nomenclature of Iron and Steel of the International Association for Testing Materials * has proposed the following definition of steel: " Iron which is cast from the molten state into a mass which is usefully malleable initially at least in some one range of temperature."

The definition excludes blister steel, which is of plastic instead of fluid origin. The committee therefore proposed the following supplementary definition of steel of plastic origin: " Iron which is aggregated from pasty particles without subsequent fusion; is malleable at least in some one range of temperature; and contains enough carbon (say 0.30 per cent or more) to harden usefully on rapid cooling from above its critical range."

413. Classifications of Steels. Steels are classified according to method of manufacture as:

Blister or cementation steel, made by the carburization of wrought iron at a bright red heat in the cementation furnace.

Crucible steel, made by the carburization of wrought iron in a molten state in crucibles.

Bessemer steel, made in the Bessemer converter by blowing finely divided air currents through molten pig iron, thereby removing the impurities in the latter.

Open-hearth steel, made by subjecting pig iron and steel scrap to the oxidizing flame of gas and air burned in a reverberatory furnace.

Electric steel, usually made by refining steel partially purified in the converter or open-hearth in the hearth of a furnace heated by electric induction, electric resistance, or the electric arc. (Some electric furnaces produce steel from pig iron and scrap, and some produce steel direct from the ore), and

Duplex steel, made by completing in the open-hearth the refinement of steel partially purified in the Bessemer converter.

Steels are classified according to carbon content as:

Soft, mild, or low-carbon steel, containing from 0.08 to 0.10 per cent carbon in the case of Bessemer steel, and 0.08 to 0.22 per cent carbon in the case of open-hearth steel.

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* Proceedings Sixth Congress of International Association for Testing Materials, 1912.

Medium or medium-carbon steel, containing from 0.18 to 0.30 per cent carbon, and

Hard or high-carbon steel, containing from 0.30 to about 1.5 per cent carbon.

Steels are also classified according to the uses for which their properties fit them as:

Boiler-rivet steel, softest, most ductile, least strength.

Structural-rivet steel, very soft, very ductile, low strength.

Boiler-plate steel, soft, ductile, medium strength.

Structural steel, medium hardness, ductility, and strength.

Machinery steel, fairly hard, less ductile, high strength.

Rail steel, hard, low ductility, high strength.

Spring steel, rather soft, low ductility, very high strength, and

Tool steel, extreme hardness, very low ductility and extremely high strength.

414. Steel as a Material of Engineering Construction. The place of steel among construction materials has been indicated above in the consideration of cast iron, malleable iron, and wrought iron. From the time of the development of cheap processes of steel production following Sir Henry Bessemer's invention of 1855, steel has held the foremost position among metallic materials of construction.

In the form of rolled sections and shapes it is almost exclusively used as a metallic structural material for the construction of frames of buildings, bridges, and all manner of structures above the ground. No other material comes in competition with rolled steel for the construction of railroad rails; as a material of machine construction, either as rolled or as cast steel, it has many applications which cannot be as advantageously served by either cast iron, malleable iron, or wrought iron; as rolled plate it is almost exclusively used for the shells of boilers, tanks, etc., for the hulls of vessels, and for the web portion of girders; as sheet steel it is used to a large extent as a cheap form of roof sheathing and both exterior and interior wall covering for buildings; special steels are exclusively used in the construction of ordinance and armor-plate; and in the form of either high-carbon steel or alloy steel it is almost absolutely without a competitor as a material for cutting tools or for springs.

The uses of steel in construction generally are so multitudinous that it is altogether impossible to indicate even in a general way its important applications. Its pre-eminence among iron products is indicated, however, by the fact that about 75 per cent of the total tonnage of iron products of the United States is steel of one form or other.

THE MANUFACTURE OF STEELS

GENERAL

415. Steel-making Processes. The making of steel was in the early days a process of conversion of iron ore into steel by direct methods whose general nature has been above indicated. Indirect methods, by the carburization of wrought iron or by the refining of pig iron, were developed at a much later date, but have almost wholly superseded the original direct methods.

Two methods of steel-making by the carburization of wrought iron have been developed and are still used: (1) the *cementation process*, which produces *blister* or *cementation steel* by the carburization of wrought iron without fusion, and (2) the *crucible process*, which produces *crucible steel* by the carburization of wrought iron in a fused condition.

The two principal methods of steel-making by the refining of pig iron (with or without the admixture of iron and steel scrap) are (1) the *Bessemer process*, which produces *Bessemer steel* by blowing finely divided air currents through molten pig iron contained in a retort-shaped furnace called a "converter," the impurities being oxidized and thus removed in the slag, carbon being subsequently added; and (2) the *open-hearth process*, which produces *open-hearth steel* by subjecting pig iron and scrap to the oxidizing flame of gas and air burned in a reverberatory regenerative furnace, carbon being restored after the removal of the oxides in the slag.

Other processes of making steel from pig iron or pig iron and scrap are usually combinations of the Bessemer process and the open-hearth process, called *duplex processes*, or combination of *electric furnace methods* with either the Bessemer or the open-hearth process.

The present relative importance of the various steel processes is indicated by the fact that about 33 per cent of the steel production of the United States in 1912 was Bessemer steel, over 66 per cent was open-hearth steel, less than 0.4 per cent was crucible steel, and about 0.06 per cent was electric steel. (Blister steel is not made to any extent outside of England, and duplex steel has been included above with open-hearth steel.)

CARBURIZATION OF WROUGHT IRON

416. The Cementation Process. The principle which underlies the operation of steel-making by the cementation process is that iron at a bright red heat will absorb carbon by an action which appears to be a traveling of solid carbon into solid iron, thereby forming a solid solution of iron and carbon.

The cementation furnace (Fig. 201), as used at Sheffield, England, consists of a brick or stone structure of rectangular plan, 15 to 20 feet long and 12 to 15 feet wide, provided with an arched roof and chimneys on either side. Manholes are provided in each end wall for charging and discharging. The entire furnace is enclosed within an outer masonry wall which continues upward as a conical hood or stack to a height of 20 to 30 feet above the furnace. The intermediate space between the furnace walls and the stack is filled with earth or sand, open passageways being provided opposite the furnace doors. Within the furnace are located two "converting pots" which are 2½ to 4 feet wide and high, 8 to 15 feet long, built of stone, and supported on short piers above the furnace floor to allow free access of the heat to all sides of the pots.

A fire is maintained in a firebox which extends the length of the furnace between the converting pots and beneath the level of the floor. A space provided beneath the grates serves as an ash pit.

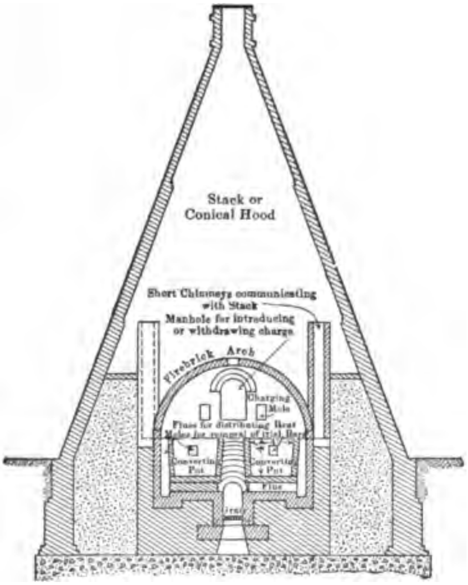

Fig. 201.—Cementation Furnace.

The bars of wrought iron which are used for the cementation process in England (very little cementation steel is made outside of England) are usually very pure Swedish iron made by the charcoal-hearth process. They are usually 2½ to 3 inches wide, ½ to ¾ inch thick, and of a length corresponding to the length of the cementation pots.

The operation of the process is begun by lining the bottom of each pot with small particles of charcoal upon which alternate layers of iron bars and charcoal are placed until the pots are filled. A space is left between the bars in each layer so that each bar is completely surrounded with charcoal. The top of the pots is now luted tight with a wet mixture called "wheel-swarf," composed largely of material derived from the wear of the grindstones in the cutlery mill. This material permits the escape of gases at first, but later becomes air-tight. The total charge of a furnace amounts to from 8 to 13 tons of iron.

The fires are now started and the required bright red heat is attained in from two to four days. The progress of the operation is tested from time to time by withdrawing and examining the fracture of trial bars which have been placed so that they project through small apertures called "moles," specially provided for the purpose in the ends of the pots.

The required temperature (650° to 700° C.), having been attained, the carbon begins to soak into the iron at a rate of about ⅜-inch per 24 hours. The time required for the completion of the process depends upon the grade of steel produced. Mild heats require the maintaining of the maximum temperature for a period of from 7 to 8 days, medium heats require about 9½ days, and high-carbon heats require about 11 days. Since the carburization proceeds from the exterior of the bars inward, the carbon content decreases progressively toward the center, and an unaltered core will be found in very mild bars. This is illustrated by the following cases:

(*a*) ½-inch bar, per cent C at outside = 0.98, per cent C at center = 0.10, ave. per cent C = 0.45;
(*b*) ½-inch bar, per cent C at outside = 1.50, per cent C at center = 1.15, ave. per cent C = 1.33.

The different grades of cementation steel made at Sheffield are classified as follows:*

No. 1.	Spring heat	0.50% C.
No. 2.	Country heat	0.63
No. 3.	Single-shear heat	0.75
No. 4.	Double-shear heat	1.00
No. 5.	Steel-through heat	1.25
No. 6.	Melting heat	1.50

When the carburization has proceeded to the desired point the fire is withdrawn, and the furnace is allowed to cool for about a week before the bars are removed.

The presence of some slag in the original wrought-iron bars is responsible for the appearance of blisters on the surface of the bars, which have been formed by the evolution of carbon-monoxide gas when the carbon combined with the ferrous oxide of the slag. The presence of these blisters accounts for the use of the term "blister-steel," which is often applied to steel made by the cementation process.

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* Bradley Stoughton, "The Metallurgy of Iron and Steel," p. 70.

THE CRUCIBLE PROCESS

417. General. Although the steel produced in very ancient times by the Chaldeans, Egyptians, or other early civilizations was probably made by methods similar to the crucible process, the actual invention of the modern crucible process was not made till 1740, when the efforts of Benjamin Huntsman of Sheffield, England, to devise a steel process superior to the cementation process, were finally crowned with success. For over one hundred years thereafter the crucible process remained the principal and almost the only method of steel-making, the cementation process being relegated to the unimportant position it has always since held, principally as an intermediate stage in the production of the finest cutlery steel, its product being remelted in crucibles.

The cost of crucible steel is very high, however, and steel was unable to supplant wrought iron as a structural material until after the invention of the Bessemer process in 1855, and the open-hearth process in 1861. In spite of the fact that Bessemer steel and open-hearth steel may be produced at a much lower cost than crucible steel, the latter still occupies a distinctive field from which the cheaper processes seem unlikely to crowd it. Its use is now restricted mainly to the making of high-grade tools and cast-steel machine parts, where first cost is less important than intrinsic quality. For these purposes it is superior to the best open-hearth steel, even though the two steels may show exactly the same composition.

The crucible process consists essentially in the melting of wrought iron in closed crucibles of refractory material, the carburizer being placed in the crucible with the iron, together with any special alloying element desired. The details of the process vary according to the type of furnace and fuel used: for the most part the gas-fired regenerative furnace is used, but in England the earlier type of coke-fired furnace is employed to a considerable extent. The two types of furnace will be briefly considered separately.

418. The Coke-Furnace or Melting-hole. The English type of coke-furnace or melting-hole is shown by Fig. 202. In the steel-melting house the melting-holes are ranged along the sides of the building below the floor level. Each hole is built of masonry to hold two crucibles. The crucibles are set directly in the fuel on short stands of refractory material which are supported by the grates. The top of each chamber is covered by a slab of firebrick set in an iron frame.

The melting temperature is maintained by controlling the chimney draught, a chimney opening being provided for the purpose below the grates. The fuel used is a hard-burned coke which completely surrounds both crucibles. The fuel must be replenished several times during the operation of melting.

The crucibles used in the melting-hole are of clay, having the general shape and size shown in Fig. 203. The making of clay crucibles must be carefully done, and, on account of the danger of cracking or excessive distortion due to shrinkage stresses, they are subjected to a long course of slow drying on shelves provided on the walls of the melting-house above the coke-holes. After drying, the crucibles are burned and carefully annealed, and are then heated up in the melting-hole before being charged. The maximum life of a clay crucible does not exceed 3 heats, after which the danger of breakage is very great, and frequently a crucible must be rejected after only one heat.

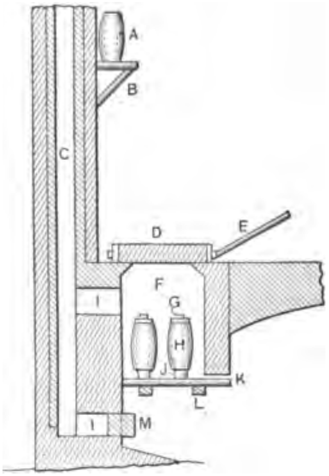

Fig. 202.—English Crucible Steel Melting-hole. (Macfarlane.)

A. Crucible being gently dried. *B*. Shelf and Support. *C*. Stack. *D*. Cover of melting hole. *E*. Handle. *F*. Furnace. *G*. Crucible lid. *H*. Crucible. *I*. Flue. J. Stand. *K*. Fire-grates. *L*. Great bearer. *M*. Stack damper..

419. The Gas-fired Regenerative Furnace. The gas-fired regenerative crucible-steel furnace is simply an adaptation of the Siemens type of furnace which is used in open-hearth steel making. The general features of the furnace are shown by Fig. 204.

The gas-fired furnace contains anywhere from two to twenty melting-holes, each large enough to hold either four or six crucibles. Six or eight inches of coke dust is placed in the bottom of each melting-hole, in the center of which a hole is provided so that, if a crucible breaks, the steel may be taken up by the coke, or will escape through the hole to the vault below, where it may be cleaned up. The melting-holes are connected on either side by means of "ports" and vertical flues or "up-takes" with chambers called "regenerators," placed on a level below the melting-holes. The regenerators are filled with a loose checker-work of brick and are connected below with flues which lead to reversible valves, whereby the passage may be made to lead to the stack upon the one hand or to the gas main or the outside air upon the other hand. Four regenerators are required for each furnace, two upon each side. The two smaller regenerators nearest the center line of the furnace are alternately used to preheat the incoming gas, while the two larger outer regenerative chambers alternately preheat the air required for combustion. While the two regenerators on one side of the furnace are preheating the incoming gas and air the gaseous products of combustion are passing out through the ports and vertical flues on the opposite side to the second pair of regenerators, to whose brickwork they give up a large part of their heat before passing on to the stack. When the gas and air valves are reversed, the current of incoming air and gas is caused to pass through the chambers which have just been heated by the burned gases, and by timing the reversals of direction of the current of gases to come about once every fifteen or twenty minutes,

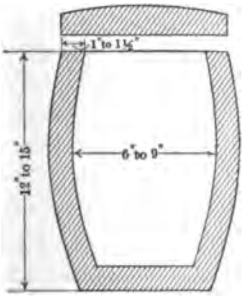

Fig. 203.—Clay Crucible.

the temperature of the incoming gases may be maintained at a fairly uniform degree. This utilization of the heat of the burned gases to preheat the incoming gases explains the use of the term " regenerative " in speaking of the Siemens furnace.

The gas used may be either natural gas or producer gas, the thermal value of the former greatly exceeding that of the latter. The arrangement of the ports must always be such that the gas enters below the air, mixing therewith as it rises in the ports.

The type of crucible used in the gas-fired furnace is not made entirely of fireclay, but is a mixture of about 50 per cent graphite, 40 per cent or more clay, and the balance silica sand. The graphite crucible costs more than clay, but it lasts longer and is stronger, thus permitting larger crucibles to be used. (The capacity is usually nearly twice that of a clay crucible).

The graphite crucible is made in practically the same manner as a clay crucible and must be burned and annealed with equal care. It is tougher than the clay when cooled, although the latter is held to be tougher at a melting heat. The average life of a graphite crucible is much greater than that of a clay crucible, however, most crucibles serving for at least three heats, and sometimes for as many as eight heats, before rejection.

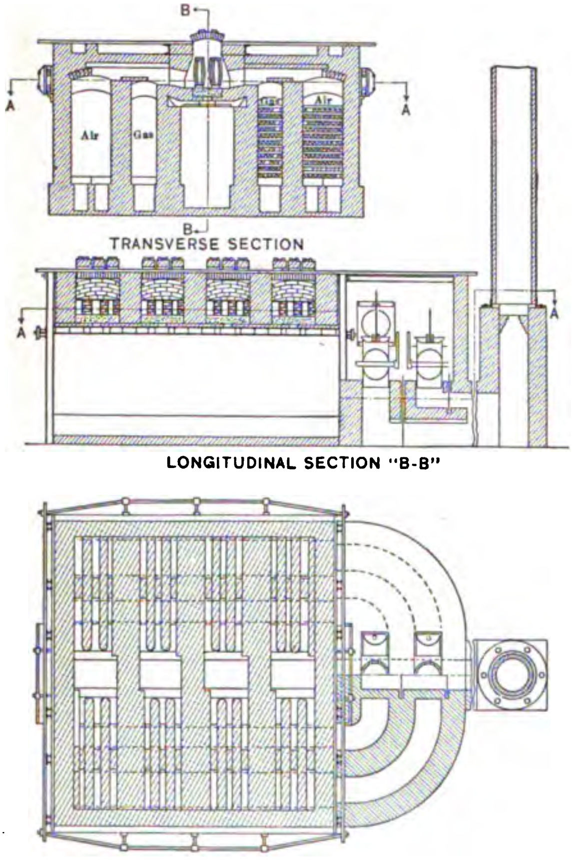

Fig. 204.—Gas-fired Regenerative Crucible Furnace.

420. The Charge of the Crucible. The crucible charge is usually about 50 pounds for a new clay crucible, but must be reduced to about 44 pounds for the second charge, and 38 pounds for the third charge, in order that the slag-line, where the wall of the crucible is attacked and weakened, may be lowered each time. The usual charge of the graphite crucible is from 85 to 100 pounds.

The English practice in charging clay crucibles is to heat the crucibles in the coke-hole and then introduce the charge through a funnel. The

American practice is to charge the crucible outside the furnace. The larger pieces of iron are first inserted, next the charcoal and ferro-manganese or oxide of manganese, and lastly the smaller pieces of iron.

The iron of the crucible charge is supposed to be pure puddled iron, but in many cases, especially in American practice, wrought-iron scrap and even soft-steel scrap is substituted for a considerable part of the charge. This practice means cheapening the process and lowering its quality. Blister steel made by the cementation process is very frequently used in place of wrought iron in English practice, and rarely in American practice. The resultant product is claimed by the Sheffield steel-makers to be so superior to any steel made that the extremely high cost is justified.

The carburizing agent used is almost invariably charcoal, which is added in small lumps. Ferro-manganese or oxide of manganese is added to aid in forming a liquid slag and to add a little manganese to the metal. Other " physics," such as salt and potassium ferro-cyanide, are sometimes used to aid in slag formation and in the absorption of carbon.

Special elements such as chromium, tungsten, manganese, vanadium, etc., are sometimes added when special steels of the class called " alloy steels " are to be produced.

421. Operation of Process. The crucibles having been charged either before or after having been placed in the melting-hole, the covers are placed upon the crucibles and the temperature is gradually brought to a melting heat by building up the coke fire to the top of the crucibles in the case of the coke-furnace, or by turning on the air and gas in the case of the gas-furnace. The process is thereafter divided into two stages called " melting " and " killing."

The melting requires from two to four hours, depending largely upon the composition of the charge. Low-carbon heats take much longer than high-carbon, since low-carbon stock melts at a much higher temperature than high-carbon. The melting time averages somewhat less with the gas-furnace than with the coke-furnace, rarely exceeding 2½ to 3 hours for the former. The fuel of the coke-furnace requires replenishing two or three times during melting down.

There is no sharp line of demarkation between the melting and the killing stage, as this is interpreted by the judgment of the melter, who removes the cover and examines the charge to make sure that it is entirely molten.

Killing or " dead melting " consists simply in holding the steel at a melting temperature until it becomes tranquil, i.e., does not evolve gases, and will pour " dead," i.e., without ebullition, and produce sound ingots. The change which occurs during killing consists either in boiling the gases out of solution in the metal, or in acquiring soundness by combination of the gases with silicon, which is reduced from the walls of the crucible by carbon. If killing be prolonged too much the usual effects of excess silicon are noted, the steel being hard, brittle, and weak. The killing time depends upon the temperature, the carbon content of the metal, and the content of silicon, sulphur, phosphorus, etc. The hotter the furnace, the lower the carbon, and the purer the metal is, the shorter will be the time required for killing. The actual time required varies according to the above conditions from about ¼ to 1¾ hours.

The total time required for the completion of the process is 3½ to 5½ hours in the English coke-furnace, and 3 to 3½ (rarely 4) hours in the gas-fired furnace. (As much as 1 hour longer may be required in using a cold crucible for the first time.)

The net results attained in the process are the addition of carbon, the elimination of slag (removed before pouring), and the addition of some silicon and manganese. Since the process is entirely an acid process no sulphur or phosphorus is removed.

When the operation of killing is complete the crucibles are gripped by a suitable pair of tongs and lifted out of the melting-hole. Usually the operation of " drawing " the crucibles is performed by a workman who must straddle the melting-hole while doing so. The use of overhead cranes with special tongs has been occasionally resorted to.

The cover is now removed and the slag floating on top of the steel is skimmed off by means of an iron rod with a ball of slag on one end, against which it chills. The steel is now poured or " teemed " into an ingot mold, any remaining slag being kept back by holding a bar against it. The mold used is of cast iron and has commonly a cross-section of 3 to 4 inches square; it is split lengthwise and is held together by rings keyed on. The surface of the mold is coated with smoke from a gas flame, or from burning coal-tar or resin, in order to prevent sticking and to improve the surface of the ingot.

The capacity of the mold is commonly that of one crucible. If more than one crucible is used for one ingot the teeming must be done in such a manner as to prevent even a momentary interruption of the stream of metal entering the mold. Otherwise the surface of the metal in the mold will freeze over, causing a serious defect called a " cold shut." In any case the teeming must be done very slowly and carefully, never permitting the stream of metal to strike the sides of the mold.

422. Grades of Crucible Steel. Very wide ranges in composition and properties of crucible steels are obtainable. The composition, in fact, is sometimes uncertain owing to the variable amount of carbon and silicon that may be absorbed from the crucible walls. Ingots are therefore always graded by breaking off the worthless upper portion containing the " pipe " and examining the fracture. An experienced man is thus able to estimate the carbon content quite closely. Chemical analysis is now usually employed to supplement examination of the fracture, and the ingots are separated into several grades of similar analysis.

No sharp subdivision of grades and uses of crucible steel can be made, but the following table shows in a general way the character of steel required for different classes of tools:

APPROXIMATE GRADING OF CRUCIBLE STEELS

(Carbon Steels Only)

Uses	Carbon %	Manganese %	Silicon %	Sulphur %	Phos. %
Battering tools..... Hot-work tools.... Dull-edge tools, etc.	.45-.65	.20-.50	.20-.30	.02-.060	.015-.050
Dies, axes, large ... drills, reamers, etc.	.65-.85	.20-.40	.20-.30	.015-.030	.012-.025
Chisels, knives..... Drills, lathe tools...	.85-1.10	.15-.30	.15-.25	.010-.020	.010-.020
Razors, fine lathe... tools and drills.... Gravers tools, etc...	1.10-1.50	.10-.25	.12-.25	.005-.015	.005-.015

423. Cost of Crucible Steels. The great difference in cost between crucible steels and Bessemer and open-hearth steels is due largely to the much greater ratio of labor expended to tonnage produced by the former processes compared with the two latter processes. The excessive fuel cost is also a contributing factor, the weight of coke fuel burned in the coke furnace being three or four times the weight of steel produced, and the weight of coal burned in gas producers for the gas-fired furnace being nearly equal to the weight of the steel produced. The high cost of crucibles and the necessity of using expensive raw materials are also important factors.

The Bessemer Process

424. Historical. The Bessemer process for the manufacture of steel was invented by Sir Henry Bessemer in England in 1855. It is doubtful if any single invention or discovery has ever had such a wonderful effect upon industry and manufacturing in general. By producing large quantities of steel at a cost far below that of any previously known process, it rendered possible the great industrial development of the world which has characterized the last fifty years.

For thirty-five years the Bessemer process led even the open-hearth process, both in tonnage produced and in perfection of methods, but the perfection of the basic open-hearth process has gradually resulted in the production of steel whose superior quality has enabled it slowly to replace Bessemer steel in one field after another, until finally in 1908 the tonnage of open-hearth steel produced in the United States exceeded the tonnage of Bessemer steel for the first time.

425. The Bessemer Process in General. The Bessemer process consists essentially in the removal of most of the impurities in pig iron by oxidation, through the agency of finely divided air currents blown through a bath of molten iron contained in a vessel called a " converter." In American practice the addition of a " recarburizer " after " blowing " is necessary to give the " blown metal " the required carbon content for steel.

The following operations constitute the essential features of the American Bessemer steel process:

(1) Molten pig iron is brought from the blast furnace plant in hot-metal ladles and discharged into a large reservoir called the " mixer." (Many of the older plants are not operated in direct conjunction with a blast-furnace plant, in which case the pig iron is remelted in large cupolas within the steel plant.)

(2) The mixer supplies molten iron as required to charging ladles, which in turn discharge into the converters, the latter being rotated into a horizontal position during charging.

(3) The air blast of the converter is started and the vessel is elevated into a vertical position. The finely divided air currents pass up through the molten metal for a period of about ten minutes, by which time the impurities will have been practically eliminated by oxidation.

(4) The converter is again turned into a horizontal position and the wind is cut off. A predetermined amount of recarburizer is now added to the bath in order to obtain a steel of any desired carbon content.

(5) The molten steel is poured from the converter into a ladle which is swung by a crane over a series of cast-iron ingot molds (mounted on cars), into which the metal is teemed.

(6) When the ingots have cooled sufficiently, the molds are stripped off and the ingots are placed in " soaking-pits " or reheating furnaces, where they remain until their still molten interiors have solidified and the temperature of the metal has become equalized throughout.

(7) The hot ingots are transferred to the rolling mills where by a series of rolls they are reduced first to " blooms " and then to any desired shape for use in construction. (Presses sometimes replace rolls.)

These operations will be further considered in the discussion which follows:

426. The Pig Iron Used. The Bessemer process universally used in American practice is an acid process, i.e., the slag formed is of an acid character. In consequence, it is impossible to remove either phosphorus or sulphur from the iron, and a grade of pig iron specially low in these elements is required. The usual limits of composition of Bessemer pig iron are:

Silicon. %	Manganese. %	Carbon. %	Phosphorus. %	Sulphur. %
1.0–2.0	0.4–0.8	3.5–4.0	0.07–0.10	0.02–0.07

At least 1.0 per cent of silicon is required in order to insure the production of a sufficient quantity of slag of satisfactory character, and also to provide heat. In fact, the oxidation of the silicon is the principal source of heat in the converter, the amount so derived being about twelve times that derived from the oxidation of the carbon and ten times that derived from the oxidation of the manganese. (Assuming the iron to have a composition corresponding to the minimum of each constituent in the above analysis.)

427. The Bessemer Converter and other Equipment of the Bessemer Plant. The Bessemer converter consists of a heavy steel sheet of cylindrical form supported upon two trunnions upon which it can be rotated.

The upper portion of the shell is conical and may either be concentric (Fig. 205), or eccentric (Fig. 206).

The former form of " nose " has now almost entirely replaced the latter. The clear opening at the converter mouth is usually from 2 feet to 2½ feet in diameter, the inside diameter of the cylindrical portion is about 8 feet, and the height from inside of bottom to " mouth " is about 15 feet.

(These dimensions apply to the average-sized converter, having a capacity of 15 tons. Converters are used, however, having capacities all the way from 1 ton to 20 tons.)

The lining of the converter is usually from 12 to 13 inches thick, and is made of very refractory material of strongly acid character, silica being the principal constituent. In American practice, ganister blocks or bricks laid with thin fireclay joints are usually employed. In England, a natural ganister rock is commonly used. The lining is repaired between heats with a mixture of silicious material and clay, and more extensive repairs are made during shut-downs. Under average conditions a lining may be made to last for several months—perhaps 10,000 to 15,000 heats—before it need be entirely replaced. A new lining must be dried, and a cold lining must be heated to a red heat before the converter is charged.

The bottom of the converter is pierced with a great number of small holes, through which the air blast enters from the " wind-box" at the bottom of the vessel. The wind-box is connected by a pipe and slip ring with a hollow trunnion which communicates with the blower. This arrangement makes it possible to put on the blast regardless of the position of the converter with respect to the normal vertical position. The trunnion opposite the hollow one carries a pinion which engages with a rack which is moved forward and backward by a hydraulic piston to rotate the converter.

The lining of the bottom is made up of damp silicious material bound together with clay in which the molded tuyere brick are set. The number of tuyeres varies from 15 to 30 and each contains from 10 to 18 holes of $\frac{3}{8}$ to $\frac{5}{8}$ inch diameter. The total thickness of the bottom lining is commonly from 24 to 30 inches.

On account of the fact that uncombined iron oxide has a strongly corrosive action on the lining, the bottom is corroded very rapidly, especially in the vicinity of the tuyeres, where the air encounters the molten iron. This limits the life of the bottom lining to about 20 or 25 heats, even though repairs are made between heats.

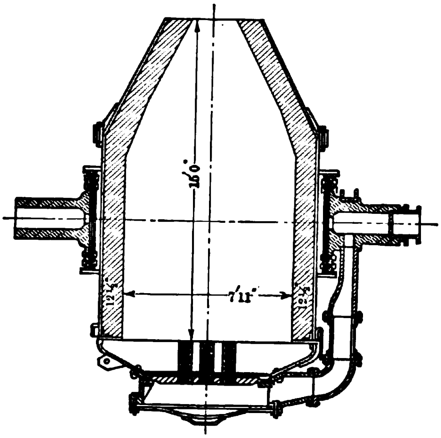

FIG. 205.—12-15 Ton Bessemer Converter. Concentric Type.

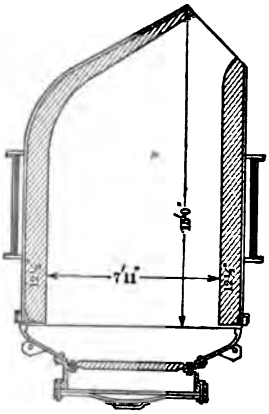

FIG. 206.—12-15 Ton Bessemer Converter. Eccentric Type.

On this account the bottom of the converter is made easily detachable, the fastenings to the body being links secured by keys which can be quickly removed. The worn out bottom is lowered by an hydraulic jack, located beneath the converter, on to a car which conveys it to the repair room. Meanwhile a new bottom on a second car is lifted into place and keyed on. The new bottom is carefully dried and heated to a high temperature before being put in place, and the joint with the body lining is daubed with mud before the bottom is forced into place by the hydraulic ram. In some cases the average time required to replace a bottom does not exceed 20 minutes.

The blast is derived from blowing engines of either the vertical or horizontal type operating on steam or, in the later installations, on blast-furnace gas. A pressure of from 20 to 30 pounds per square inch is maintained. The turning on and off of the blast, as well as the movement of the converter, is all under the control of the "blower" who stands on a raised platform called the "pulpit" within full view of the entire operation.

If the Bessemer plant is not operated in conjunction with a blast furnace the pig iron is melted in cupolas which differ in no respect from the ordinary foundry cupola except in size, the usual dimensions being from 8 to 12 feet in internal diameter and 40 to 60 feet in height. Usually from 3 to 6 cupolas are required for a Bessemer plant. The cupolas are commonly worked continuously for several days or a week, after which time they must be closed down to remove the " scaffolds " and make necessary repairs. The metal is tapped at intervals into ladles which convey it directly to the converter.

More commonly, in recent years, the pig iron is run into ladles at the blast furnace, and transferred (perhaps a considerable distance) to the steel plant, where the ladles are lifted by a traveling crane and discharged into the mixer, which serves as a source of supply for the converters.

The mixer (Fig. 207) is simply a large steel reservoir lined with refractory brick and mounted on rollers. Hydraulic cylinders located at the corners serve to tip the mixer to pour out the metal. The capacity of the mixer is from 150 to 500 tons. Because of its large size the mixer will hold the product of several furnaces, and tends to average the irregularities in the different irons, thus lessening the variability of the converter charge. The mixer also serves to keep the pig iron molten for an indefinite length of time, compensates for delays either at the blast furnace or at the steel plant, and affords an opportunity for the addition of special pig iron, if necessary to correct the composition.

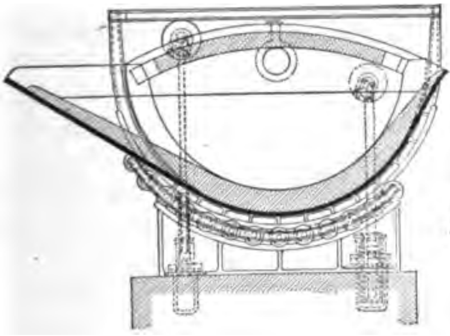

FIG. 207.—Metal Mixer.

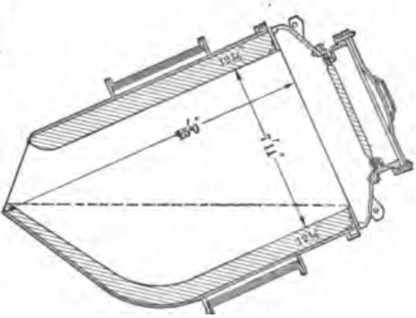

FIG. 208.—Position of Converter while Receiving Charge.

When a converter is to be charged, a ladle on a car is run under the pouring spout of the mixer and metal is poured into the ladle until the latter contains the amount required for a converter charge, as indicated by the track scales upon which the ladle car rests. The ladle car is now transferred to a point opposite the converter, the latter is rotated to a nearly horizontal position, and the charge is poured in.

428. Operation of Process. The position of the converter while receiving its charge is shown by Fig. 208. The concentric converter may be charged from either side, but the eccentric converter is always inclined in the same direction. The bath of metal never reaches the height of the tuyeres before the vessel is righted, and the blast is turned on after charging and before righting in order to prevent the metal from entering the tuyeres. The bath of metal occupies only a small portion of the volume of the converter (perhaps 18 inches depth in a 15-ton converter), on account of the great increase in the volume of the bath caused by the violent ebullition of the metal during the blow.

After two or three minutes a reddish-yellow flame begins to pour from the mouth of the converter, indicating the beginning of the oxidation of carbon. This flame becomes rapidly augmented until a white-hot flame, 20 to 30 feet in height, pours out with a loud roaring sound, and a shower of sparks appears, owing to the ejection of slag and metal. Soon the flame begins to flicker and shorten, indicating that the carbon is practically burned out, whereupon the converter is immediately turned down and the blast shut off.

429. Chemistry of Process. Under the extremely active oxidizing influence of air driven through the bath of molten metal, all of the elements are oxidized, almost without regard to their relative affinities for oxygen.

Thereupon the slag formed by oxidized iron and other elements possessing a lesser affinity for oxygen, attacks the more easily oxidized elements and the latter become eliminated first.

As soon as the blow is on the silicon and the manganese begin to be burned to SiO_2 and MnO, the action being partly direct oxidation by the oxygen of the blast, and partly indirect through the agency of the FeO, and the CO which are easily robbed of their oxygen. Some iron oxide always survives, however, and with the silica forms a silicate of iron, $FeSiO_3$, which is in large part retained in the slag. Additional iron oxide is dissolved in the slag formed by ferrous silicate and manganese silicate, but a portion of this dissolved iron oxide is later reduced by carbon and manganese contained in the recarburizer.

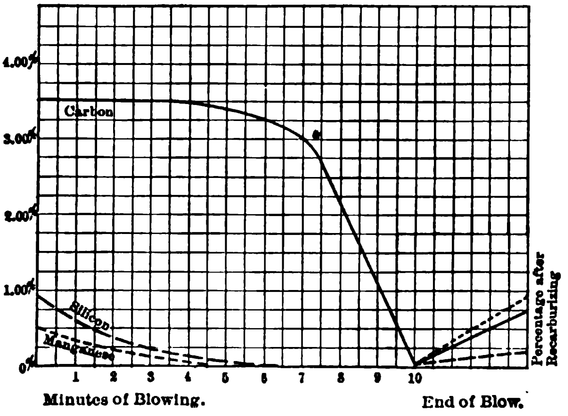

FIG. 209.—Removal of Impurities in Acid Bessemer Process. (Bradley Stoughton.)

The sequence of the removals of silicon, manganese and carbon is shown in the diagram of Fig. 209. It will be noted that the silicon and the manganese have been reduced to mere traces before the loss of carbon becomes appreciable. The carbon begins to become oxidized after about

$2\frac{1}{2}$ to 3 minutes, this being the only chemical action taking place after the silicon is eliminated until the blow is stopped and the recarburizer added. The addition of the recarburizer results in the increase of manganese and carbon, and of silicon to a lesser degree.

The phosphorus and the sulphur will not have been affected by the process, but the percentage present in the blown metal will be slightly higher than in the pig iron because of the loss of other elements (amounting to 8 to 10 per cent of the original weight) which have been carried away in the slag.

The total time required for the blow is, in American practice, from nine to ten minutes. In English and German practice, especially in using high silicon irons, the blow is often considerably longer.

The amount of air used in the blast per minute is from 15,000 to 30,000 cubic feet, which means that from 3000 to 6000 cubic feet of oxygen per minute are utilized.

430. Heat Development and Utilization. Silicon is the greatest source of heat in the acid Bessemer process and if the silicon in the iron be too low the result will be a cold blow. The oxidation of 1 per cent of silicon results in raising the temperature of the bath about 188° C. (Richards). Manganese is about one-fourth as effective, while the oxidation of iron produces only about one-sixth the heat derived from the oxidation of an equal amount of silicon. Carbon, because of the fact that it is only burned to carbon-monoxide in the converter, contributes practically nothing to the net heat gained by the bath. (The above statements refer to the net gain in heat after deductions have been made to allow for losses to the vessel, air, etc.) A slight additional amount of heat is derived from the combination of oxides of iron and manganese with silica to form the slag.

The temperature of the bath upon entering the converter will be in the neighborhood of 1250° C., and the maximum temperature will be about 1600° C. The average temperature during the operation will be about 1500° C. Occasionally it is necessary to cool the bath by admitting live steam with the blast.

431. Recarburizers and Recarburizing. The principal recarburizers used are " spiegeleisen " and ferro-manganese. Speigeleisen is simply a special pig iron especially high in manganese and carbon. The manganese content varies from 12 to 20 per cent and the carbon from 4 to 6 per cent. Iron alloys containing 20 per cent or more of manganese are classed as " ferro-manganese," but practically all of that which is used as a recarburizer contains about 80 per cent manganese and 6.5 to 7 per cent carbon. Spiegeleisen is always added in a molten state because it is necessary to use large amounts (perhaps as much as 10 per cent), and the bath would otherwise be cooled too much before pouring. For this reason small auxiliary spiegel-melting cupolas are a necessary feature of Bessemer plants.

Ferro-manganese is used to produce very soft steel, such as that used for welded pipes, soft wire, etc. It need not be molten, but is usually heated to redness before being used. The amount required for a 15-ton charge will be only about 500 pounds, or about 1.7 per cent. The steel produced is low in carbon and very low in silicon.

The recarburizer was formerly not added until the blown metal had been poured out into the ladle. At present, however, the practice is to add the spiegel to the bath just before pouring, the converter being held in a horizontal position at the time. Ferro-manganese is still sometimes added in the ladle.

432. Deoxidation. The addition of the desired amount of carbon to the blown metal is by no means the only important function served by the spiegeleisen or ferro-manganese. Blown metal invariably contains considerable amounts of oxides of carbon and iron. The CO gas is somewhat soluble in the molten metal and, even though a great part of it is removed when the spiegel is added, it continues to be evolved until the metal becomes solidified. The imprisoned CO means the presence of blow-holes in the ingots of steel.

Iron oxide is reduced principally by the manganese of the recarburizer. It is also reduced by the carbon and the silicon of the spiegel, however. The silicon is also very effective in reducing the carbon-monoxide gas, thereby becoming an important factor in the prevention of blow-holes.

Sometimes especially strong deoxidizing agents are used in addition to the recarburizer to eliminate the last traces of oxides in the steel. An important instance of such a practice is the addition of titanium to steel for railroad rails. This treatment is attended with marked beneficial effects upon the quality of the steel produced.

433. Casting the Ingots. When the reaction between the blown metal and the recarburizer is complete, the steel is poured from the converter into a " teeming ladle " which is suspended from either an electric traveling crane or an hydraulic swinging crane. The teeming ladle, Fig. 210, consists of a bucket-shaped steel shell, lined with refractory material and provided with a valve in the bottom through which the molten metal is teemed. The lining is of cheap material because the nozzle is burned out in from four to six heats. The ladle is suspended by a bale and mounted in such a manner that it may be tipped over to pour out the slag which remains in the vessel after the steel has been teemed off. The ingots are cast in cast-iron molds which are mounted on cars which are moved along a continuous track entirely through the steel mill. The usual type of Bessemer ingot mold is shown in Fig. 211. The ingot produced is about 7 feet high, has an average cross-section of about 18 by 18 inches, and is about 3 inches thicker at the base than at the top in order to facilitate the stripping off of the mold.

The mold cars are moved along in such a manner as to bring each mold in succession under the nozzle of the ladle. The plunger is raised, allowing a thin stream of metal to flow into the mold, then dropped while a new mold is brought into place. The slag floats on top of the steel, and the valve is closed when slag begins to flow and the ladle is swung over a slag car and dumped. The appearance of the lining at this time gives an indication of the temperature of the metal. The metal should be found adhering to the lining in isolated spots only; a continuous coating indicates too cold metal, while a clean lining indicates too hot metal.

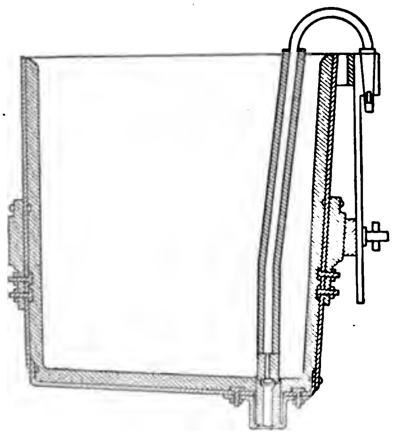

FIG. 210.—Steel Teeming Ladle.

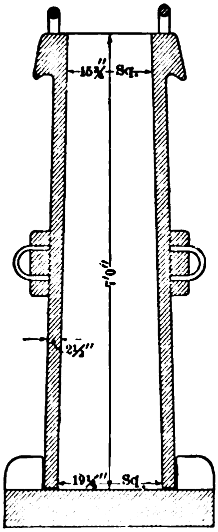

FIG. 211.—Ingot Mold.

The mold cars are drawn outside the steel mill, where the molds are stripped off by an electric or hydraulic crane, which engages the lugs provided on the molds and lifts them off, leaving the ingots standing on the iron stools which form the bottom to the mold. The ingots are now taken on cars to the "soaking pits," while the molds are washed with clay water (which dries on and forms a film which prevents adhesion of the ingot to the mold), allowed to cool somewhat, and run back into the mill for another cast. If the molds are not still hot from a previous heat, they must be heated before being used. The average life of a mold is about 100 heats, after which they become badly cracked.

THE BASIC BESSEMER PROCESS

434. General. The basic Bessemer process differs from the acid Bessemer process only because of the different class of iron used. Basic Bessemer iron is fairly high in phosphorus, and perhaps also high in sulphur, and, since the removal of these elements is possible only in the presence of a basic slag, the addition of a certain amount of lime to the charge is nécessary in order to more than neutralize the acid constituents in the iron. The fact that the slag is thus rendered basic in character makes it necessary to provide a basic lining for the converter in order that the lining may not be attacked and quickly destroyed by the slag.

The basic Bessemer process has never been used successfully in America, owing to the relative availability of high-grade ore suitable for the cheaper acid Bessemer process. In Germany, however, and in England, the conditions as to ore supply are just the reverse, and in consequence the basic process is the principal Bessemer process in use abroad.

The basic Bessemer process was first made a practicable success by two Englishmen, Sidney Thomas and Percy Gilchrist, in 1877, after many years of experimenting, and the process is often called the "Thomas-Gilchrist Process."

435. The Basic Converter. The basic converter differs in no respect from the acid converter except in the character of the lining, and the further fact that the converter must be considerably larger than the acid converter of the same capacity, on account of the increased amount of slag formed.

The lining is sometimes made up of basic bricks laid in a mortar of similar character, but more commonly it is made up of a mixture of calcined dolomite with about 10 per cent of anhydrous tar used as a binder, the material being molded in place while hot by the use of a pattern. The tuyere holes in the bottom are commonly simply cored out by packing the bottom lining around wooden pins which are subsequently withdrawn.

The basic lining is much less durable than an acid lining, the average life of a lining being commonly from 100 to 200 heats, while the bottoms are good for from 20 to 40 heats.

436. The Pig Iron Used. Basic Bessemer pig iron is high in phosphorus, manganese, and usually sulphur, and relatively low in carbon and silicon. The usual limits of composition are:

Phosphorus. %	Sulphur. %	Manganese. %	Carbon. %	Silicon. %
1.0–3.0	0.02–0.30	0.3–2.0	2.75–3.5	0.2–1.0

If the phosphorus is not high the charge is apt to blow cold after the elimination of carbon. High manganese is desired to aid the silicon in producing heat at the beginning of the blow, and to facilitate the removal of sulphur which is apt to be high because of the low silicon content. The relatively low carbon content is an inevitable consequence of the presence of high manganese and phosphorus and low silicon. Only sufficient silicon to prevent too high sulphur is desirable since, with the high phosphorus content, there would be danger of producing an acid slag if the silicon were not kept low. In any event the amount of lime required to flux the acid-making constituents, phosphorus and silicon, will be increased by increasing the content of these elements.

437. Operation of Basic Process. Chemistry of Process. The basic process is divided into two more or less distinct stages. The first, called the "fore-blow," is characterized by the oxidation of silicon, manganese, and carbon, and corresponds to the ordinary blow of the acid Bessemer process. The phosphorus and most of the sulphur are removed and absorbed by the slag during a later period called the "after blow."

Silicon, being low originally, is usually eliminated within two minutes or less, but manganese is removed very slowly because a large quantity is present and the slag is not of such a character as to take it up readily. Often some manganese is left in the iron at the end of the blow and is available for deoxidation.

Carbon is oxidized after the elimination of silicon, the removal being accomplished in slightly less time than in the acid process because of the lesser amount present.

Phosphorus is not materially reduced in amount until the carbon is practically eliminated, when it becomes oxidized and is absorbed by the slag as a phosphate of lime. A certain amount of the sulphur is also absorbed by the slag as CaS at this time. The manganese facilitates the removal of sulphur, probably by the formation of sulphide of manganese. The sequence of removals of impurities is shown graphically by Fig. 212.

The quantity of lime required to make the slag sufficiently basic will, of course, vary as the composition of the iron varies, as noted above. In general, however, the amount required will be from 12 to 20 per cent by weight of the charge. The lime is always charged before beginning the blow.

The time required for the conversion process with the basic converter is nearly double the time required for the acid process. The fore-blow requires from nine to twelve minutes, and the after-blow from five to six minutes. There is no indication, so far as the flame is concerned, of the completion of the after-blow, and the duration of this period is governed entirely by experience with the different irons used.

The silicon is principally depended upon to supply heat at the beginning of the process, and manganese is also an important source of heat in the early part of the blow. The oxidation of iron also supplies a certain amount of heat, but the phosphorus is the principal source, the heat developed from its oxidation being four or five times as much as that from any other source. The heat of oxidation of the carbon is largely lost by escaping from the converter mouth, as in the case of the acid process. The total heat developed in the basic Bessemer process is at least twice that developed in the acid process. But there is no greater net gain in temperature than in the acid process, because of the heat utilized in melting the flux and the increased loss to the vessel and the air because of the longer time required for the blow.

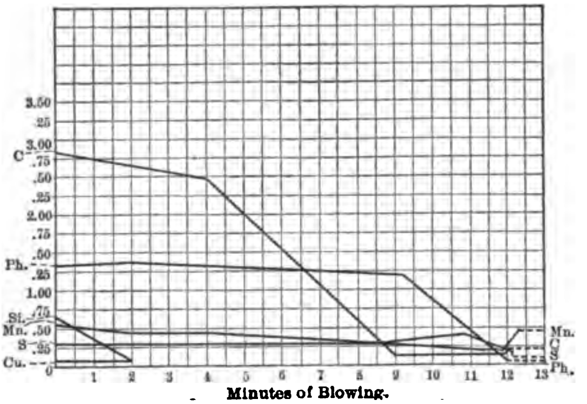

FIG. 212.—Removal of Impurities in Basic Bessemer Process. (Bradley Stoughton.)

438. Recarburization. The manner of using a recarburizer in the basic process differs from that used in the acid process, because if the spiegel is added to a bath containing a great quantity of basic slag, the carbon, silicon, and manganese of the recarburizer will reduce phosphorus from the slag and restore it to the metal.

As much as possible of the basic slag is therefore poured out of the converter first, and later, as the metal is poured into the teeming ladle, a further quantity of the slag is held back and retained in the vessel. The recarburizer is then added in the ladle, and its action is thereafter similar to that noted in the case of the acid process. The deoxidizing effect of the recarburizer is no less important in the basic than in the acid process, for the oxidation of iron in the basic converter is apt to be excessive.

439. Comparison of Acid and Basic Bessemer Processes. The acid process requires the use of a higher grade of ore and one which is almost unobtainable in some countries, particularly Germany. The basic process, upon the other hand, requires a cheap ore to be commercially successful, because the process itself is expensive.

The basic process requires a high degree of skill, because of the danger of excessive oxidation and also the restoration of phosphorus to the bath through the action of manganese in the recarburizer.

The basic Bessemer steel made by skilled German steel-makers excels the American acid Bessemer steel in quality, but is more expensive on account of the less rapid operation, the more expensive and less durable converter lining, the extra cost of lime for the flux, and the extra labor cost involved in the more complicated operation of separating the metal from the slag and adding the recarburizer.

THE OPEN-HEARTH PROCESS

General

440. Historical. The modern process of steel-making by the open-hearth method has been developed from the early work of two Englishmen, the Siemens brothers, who invented and patented the regenerative furnace in 1861. Sir William Siemens developed and perfected the early forms of regenerative furnace, and to him is credited the discovery of the practicable possibility of utilization of the regenerative principle, which alone renders possible the attainment of the very high temperatures required for the making of steel in the open-hearth.

Siemens' efforts were entirely directed toward the reduction of iron ore in a bath of pig iron, and were therefore the forerunners of the later " pig-and-ore process." In 1864 the Martins, French steel-makers, patented a process of making steel in the Siemens furnace by using pig iron and steel scrap. This process, known as the " Martin " or " Martin-Siemens " process in most parts of Europe, and in England and the United States as the " Siemens-Martin " or, more generally of late years, simply as the open-hearth process, came in time to be much more commonly used than the pig-and-ore process. The present-day practice consists in using a charge of pig iron and scrap for the most part, a certain amount of ore being added, however, for the sake of hastening the process.

The open-hearth process developed more slowly than the Bessemer process, but now ranks first among the various methods of steel manufacture, both in metallurgical perfection and in tonnage produced. It is gradually replacing the Bessemer process, even in the special fields where that process has held undisputed sway for many years, as for instance in the manufacture of railroad rails, a majority of the larger sized rails being now rolled from open-hearth steel.

Open-hearth steel is now exclusively used for all except the cheapest grades of plate steel, forgings, axles, structural steel, rods, wires, etc. It is also used to a large extent in the production of ordinance and armorplate, and for many special steels of the class known as alloy steels. The time when the Bessemer converter shall have been relegated to the place of simply an adjunct of the open-hearth in some form of "duplex process" appears not to be far distant. In this connection it is interesting to note that no plants equipped for the production of steel by the Bessemer converter alone have been constructed since 1904.

441. The Open-hearth Process in General. The open-hearth process is so called because it consists in the oxidation and removal of impurities contained in a bath of metallic iron lying on the hearth of a reverberatory regenerative furnace, the bath being exposed to the action of the flame which sweeps across above the hearth.

As in the case of the Bessemer process, there are two modifications of the open-hearth process, depending upon the character of the charge and the slag produced. The acid open-hearth process is so conducted as to produce an acid slag, accomplishing the removal of silicon, manganese, and carbon. The lining of the furnace must therefore be of acid character. The basic process involves the use of a basic flux and the production of a basic slag, with removals of not only silicon, manganese, and carbon, but also phosphorus and a part of the sulphur. The lining is necessarily basic. Unlike the Bessemer process, which is used only as an acid process in this country, the open-hearth method is conducted both as an acid and as a basic process, but the basic process greatly predominates, the tonnage of basic open-hearth steel produced being about fifteen times the tonnage of acid steel.

The open-hearth process differs remarkably from the Bessemer process in the strength of the deoxidizing agencies, and since the action is much less violent and rapid, requires a time of about ten hours as compared with about ten minutes. The furnace capacity is at least four times that of the converter, however, being from 50 to 200 tons.

The open-hearth furnace is charged with pig iron (either solid or molten) and scrap steel (always solid), and the operation of the process started by admitting a current of preheated gas and air which burn within the hearth chamber. Much heat is reflected from the arched roof and the walls. The oxidation of the impurities is a source of a certain amount of heat, but the greater part is derived from the combustion of the gas fuel. A certain amount of ore is added during the process to provide additional oxides, and additional pig iron may be added if there is danger of the original carbon becoming low too early in the heat to maintain the required temperature until the end of the operation.

The furnace is tapped through a spout by either opening a tap-hole or by tilting the furnace, the spout in the latter case being located above the normal level of the bath of metal.

442. The Open-hearth Plant. Fig. 213 presents a cross-sectional view of a typical open-hearth plant wherein the stationary type of furnace is used, and Fig. 214 is a similar cross-section of a plant using the tilting type of furnace. (The lettering on these two figures is uniform.) The furnace charge is brought onto the charging platform in steel boxes, *A*, three or four of which are supported on a car which runs on a track close up to the charging doors in the front walls of the furnaces. Each box holds about 2½ tons of metal.

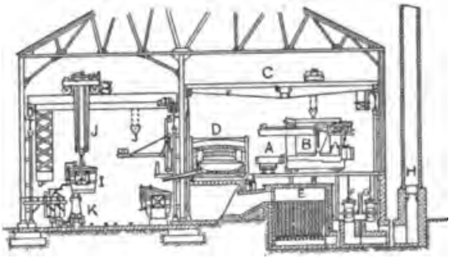

FIG. 213.—Section of Open-hearth Plant. Stationary Furnace.

Just in front of the track on which the cars above mentioned operate, is located the charging machine, *B*. Two types of charging machine are common—the high type shown in Fig. 213 and the low type shown in Fig. 214. In either case the essential part of the machine is the "ram," which engages the end of the charging-box casting, lifts same, thrusts it forward through the charging door of the furnace, and turns

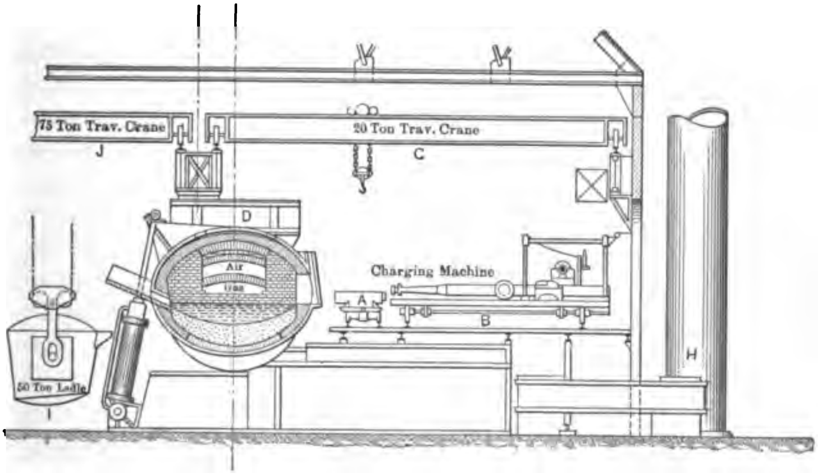

FIG. 214.—Section of Open-hearth Plant. Tilting Furnace.

it over, discharging the contents onto the hearth. The charging machine is mounted on rails, is electrically operated, and serves several furnaces.

An overhead crane, *C*, is commonly provided above the charging platform and a charging ladle is swung therefrom if molten metal forms a part of the charge.

The furnace itself is shown at *D*, the regenerators, at *E*, the gas valve at *F*, the air valve at *G*, and the stack at *H*. The casting ladle is shown at *I*, the casting crane at *J*, and the ingot molds mounted on cars at *K*.

The Furnace and its Operation

443. General Features of the Regenerative Furnace. The great difference in principle between the puddling furnace and the air furnace on the one hand, and the open-hearth furnace on the other hand, lies in the utilization by the latter of the regenerative principle with gas fuel. By preheating the gas and the air used for combustion, by means of the heat carried out of the melting-chamber by the burned gases, a great increase in thermal efficiency is gained and the furnace temperature attainable is immensely increased.

The arrangement of a furnace to utilize the regenerative principle is shown by the diagram of Fig. 215.* The melting-chamber or hearth is shown in the upper central portion of the figure. On either side are the openings called "ports," through which the gas and air enter the melting-chamber, and the vertical flues which lead to the regenerative chambers. Two regenerative chambers or "regenerators" are provided on each side of the furnace, the larger and outermost one being used to preheat the air required for combustion, while the smaller inner chamber is heating gas. Each regenerator is filled with a checker-work of brick through which the gas and air pass. Before starting up a cold furnace these regenerators are heated by fires built in the flues beneath.

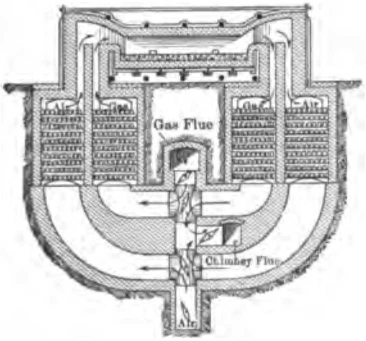

Fig. 215.—Diagram of Regenerative Furnace. (Stoughton.)

Supposing that the gas and air valves are in the position shown in Fig. 215, the direction of circulation of the gases is indicated by the arrows. Gas enters the inner regenerator on the left-hand side and passes through the bricks of the checker-work, which give up a portion of their heat, raising the temperature of the gas to about 1000° C.

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[*] Bradley Stoughton, "The Metallurgy of Iron and Steel."

At the port the hot gas encounters the current of air which has been similarly heated in passing through the outer regenerator, mixes therewith, and burns within the melting-chamber. The burned gases are then caught by the stack draught and drawn out through the ports on the right-hand side. Passing downward through the regenerators, a large part of the heat of the gases is taken up by the checker-work, the upper portion of which attains a temperature of about 1000° C. The gases leave the regenerators at a temperature which should not exceed 400° C., and pass through flues which lead to the stack.

By reversal of the valves the direction of flow of the air and gases may be exactly reversed, so that, as soon as one set of regenerators begins to be cooled too much, the incoming gas and air may be sent through the other set, which has just been heated by the burned gases. By reversing the direction of the currents about every twenty minutes the temperature of the melting-chamber may be maintained at a fairly constant point, in the neighborhood of 1600° to 1700° C.

444. Construction of Open-hearth Furnace. Fig. 215 is simply a diagrammatic representation of a regenerative furnace, such a relative arrangement of flues, regenerators, and melting-chamber not being a practical one for actual construction or use.

Two common forms of open-hearth furnaces find wide application in the steel industry. The earliest, and still most generally used type, is the stationary furnace. The tilting or rolling furnace is a comparatively recent development in furnace design, but has been adopted in many important installations. These two types of furnaces will be separately described.

(*a*) *Stationary Open-hearth Furnace.* The usual type of stationary furnace is shown by Figs. 216*a* and 216*b* in transverse section, and by Fig. 216*c* in longitudinal section. The melting-chamber is a rectangular structure built of brick masonry and supported upon either a solid masonry foundation or on beams and piers. It is reinforced with buckstays, bearing-plates, and tie-rods, and is lined with refractory material of suitable chemical nature to resist the attack of the materials which come in contact with it. The hearth is built in the form of a shallow dish and has a capacity of from 15 to 100 tons of metal. (A few furnaces with capacities ranging up to 200 tons have been built.) The 50-ton furnace is the favorite size for large works, and the depth of the bath is from 18 to 24 inches.

If the furnace is intended for use in the acid process, the hearth is built of fireclay bricks overlaid with a layer of silica about 18 inches thick. The silica is applied as silica sand, which is spread in thin layers, each layer being exposed to the full heat of the furnace and brought to the sintering point before the application of the next layer.

The basic furnace is built of magnesite bricks overlaid with a mixture of calcined magnesite and about 10 per cent of anhydrous tar. The lining is placed in layers and burned in place as in the case of the acid furnace.

One or more large charging doors are provided in the front wall of the furnace just above the level of the top of the hearth lining, and an inclined spout leads from the lowest portion of the hearth to the back or pouring side of the furnace.

The side walls of the melting-chamber and the arched roof are made of silica bricks, the most refractory material that can be otbained, laid with almost no mortar in the joints. The roof is arched from front to back and its skewbacks are supported upon steel channels, which practically carry the weight of the roof independently of the side walls. In lining the basic furnace a layer of neutral chromite brick is usually placed between the silica bricks of the side walls and the basic hearth.

The ports are designed with great care in order that the flames may neither impinge upon the bath, thereby oxidizing it excessively, nor upon the roof, which would quickly be burned out. The gas ports are always located beneath the air ports, in order that the bath may not be oxidized excessively by direct contact with the air, and also to promote a better mixing of gas and air, since the gas is lighter and therefore rises. The masonry of the ports is built of silica bricks and the floor is commonly covered with a layer of neutral chrome ore. The port area required for air is about twice that required for gas, the area of the openings at each end of the furnace being about 18 square feet for the former and 8 to 10 square feet for the latter (the furnace being of 50 tons capacity).

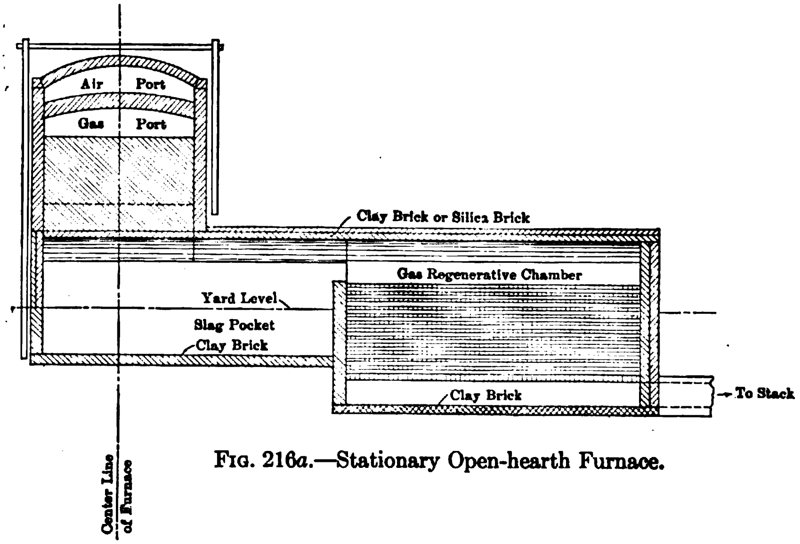


FIG. 216*a*.—Stationary Open-hearth Furnace.

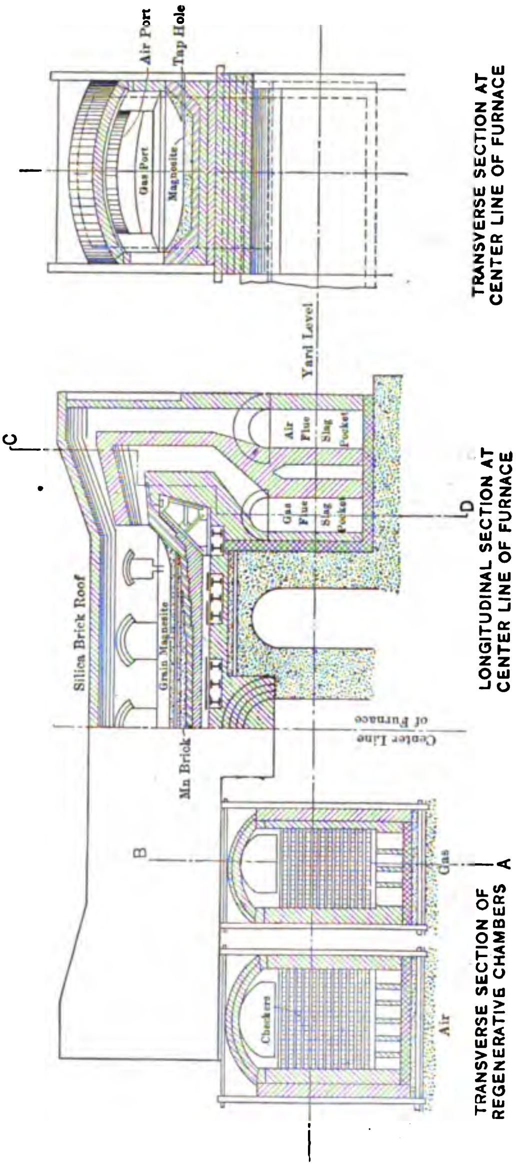
In order to prevent the carrying of dust and slag into the regenerators, the vertical flues from the ports do not lead directly to the regenerators, but to chambers called "slag-pockets" which are located on a level with the regenerators some 15 or 20 feet below the melting-chamber.

The regenerators are very large in proportion to the melting-chamber, and are nearly filled with the checker-work of bricks which serves to absorb heat from the outgoing gases and preheat the incoming gas and air. The total open space through the checker-work must considerably exceed the area of the ports because of the friction offered to the passage of the gases. The flues beneath the regenerators are large in order to distribute the incoming gas and air uniformly, and several longitudinal walls are provided in the flues for the purpose of supporting the lower tiles of the checker-work. The combined volume of the four regenerators of a 50-ton furnace amounts to about 10,000 cubic feet, the air regenerator being about one-third larger than the gas regenerator.

The usual arrangement of flues and valves is similar to that shown in Fig. 204. The gas flues leading from the regenerators converge toward the gas valve, which is set over the stack flue on the center-line of the furnace installation. A common type of water-sealed valve is shown in Fig. 217. The base-plate of the valve holds several inches of water into which the shell of the valve and the movable diverting hood project. The opening to the stack flue is shown at *b* and the two gas flues at *c c*. By reversing the arms which carry the hood by means of the outside lever, the hood may be shifted in such a manner as to afford a sealed outlet from either gas flue to the stack flue, the incoming gas—which enters the valve through a pipe at the top—being at the same time diverted to the flue not covered by the hood.

Similarly, the air flues converge to the air valve, which is also set over the stack flue, and which acts in exactly the same manner as the gas valve above described. A common type of air valve, called the "butterfly" valve, is shown in Fig. 218.

From the valves the waste gases pass directly to the stack, which must have sufficient draught to exhaust the melting-chamber and draw the gases through the regenerators, flues, and valves. Often one stack is made to serve two furnaces, stack dampers being placed in the flues thereto.



TRANSVERSE SECTION AT CENTER LINE OF FURNACE

FIG. 216*b*.

LONGITUDINAL SECTION AT CENTER LINE OF FURNACE

TRANSVERSE SECTION OF REGENERATIVE CHAMBERS

FIG. 216*c*. Stationary Open-hearth Furnace.

(*b*) *Tilting or Rolling Furnaces.* The tilting or rolling furnace of the Wellman type is shown in Fig. 219*a* (transverse section), and in Fig. 219*b* (longitudinal section). The furnace consists of a heavy steel casing of rectangular form, lined with masonry like the stationary furnace, but mounted on two steel rockers which rest upon heavy bed-castings. Two large hydraulic cylinders on the pouring side of the furnace serve to rock the furnace forward or backward during the operation of pouring.

The interior of the melting-chamber of the tilting furnace differs in scarcely any respect from that of the stationary furnace except that the spout is located above the level of the bath until the furnace is tilted on its rollers, and the design of the port opening is different. A cast-iron water-cooled ring is fitted around the port openings on the outside, and matches a similar ring on the port. The ports are built inside a heavy steel framework and are mounted on wheels or tracks carried by the up-takes from the regenerators. When it is desired to tilt the furnace, the ports are drawn back away from the furnace ends and, since the port openings are exposed while the furnace is in its tilted position, the gas and air supply must be stopped during the operation.

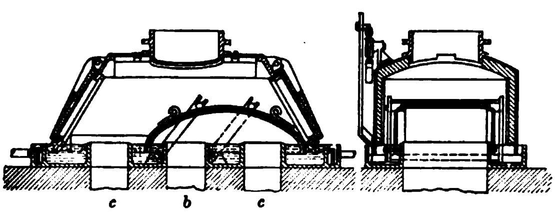


FIG. 217.—Water-sealed Gas Valve.

A common adjunct of the rolling furnace is the "fore-hearth," a substitute for a teeming ladle, which is bolted on in place of a pouring spout on the back of the furnace. The fore-hearth resembles a teeming ladle in its design and is provided with two teeming valves through which the metal is discharged into ingot molds while the furnace is in its pouring position.

The design and arrangement of the slag-pockets, regenerators, valves, and flues for the rolling furnace differs in no essential respect from that of the stationary furnace above described.

445. Stationary vs. Tilting Furnaces. The stationary furnace is less complicated in its design and requires less elaborate equipment for its operation. It is less expensive to install, and the cost of its upkeep is much less. On the other hand, the tilting furnace has the advantage of never causing delay and consequent oxidation of the bath, owing to difficulty in clearing the tap-hole; the slag can be poured off at any time, which is a great advantage in the basic furnace especially; repairs to the hearth bottom may be made with much greater facility between or even during heats; metal may be poured off at any time and transferred between furnaces (a necessary operation in the Talbot process, later described); and boiling and violent action during pouring is lessened by the chilling of the metal caused by the entrance of cold air through the open ports.

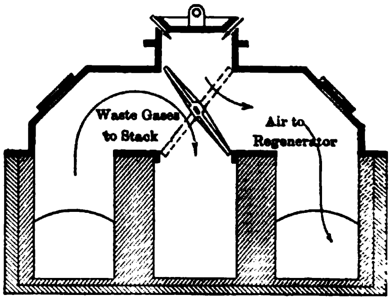


FIG. 218.—Siemens Air Valve.

446. Life of Furnace and Repairs. The life of the open-hearth furnace is extremely variable, depending upon the quality of the materials used and the management of the furnace. The ports are usually the first portion to become excessively injured and often need replacement long before the furnace must be entirely rebuilt. The removable ports of the tilting furnace have a special advantage on this account.

The bottom usually requires repairs in spots between heats, and is more extensively repaired during temporary shutdowns. In this way this bottom lasts almost indefinitely.

The roof of the furnace fails sooner or later by burning through in spots or by falling in. When this happens the furnace must be practically rebuilt.

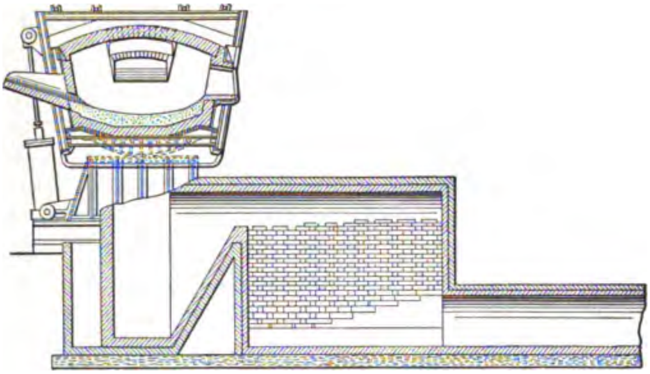


FIG. 219a.—The Wellman Tilting Open-hearth Furnace. Transverse Section.

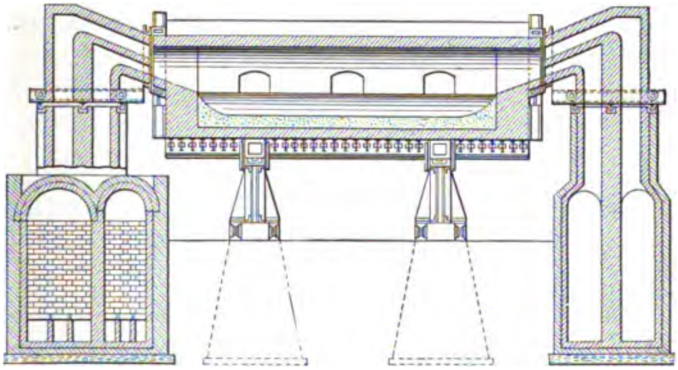


FIG. 219b.—The Wellman Tilting Open-hearth Furnace. Longitudinal Section.

The regenerators finally give out, either by becoming choked up with dust, or by cracks opening up in the walls. A shutdown is required in either case.

In general the life of a furnace is from 200 to 600 heats, averaging about 350 heats, or from three to six or eight months' operation. The acid furnace lasts longer, from 800 to 1200 heats, or from ten to sixteen months.

The Furnace Fuel

447. Natural-gas Fuel. Natural gas is the ideal fuel for the operation of the open-hearth furnace, but its use is necessarily limited to the vicinities of the somewhat restricted districts of Pennsylvania, Ohio, West Virginia, etc., where it is available.

Natural gas is essentially marsh gas or methane, CH_4, with varying admixtures of other members of this series of hydrocarbon gases, together with hydrogen. It usually contains 60 to 80 per cent of methane and 20 to 30 per cent of hydrogen. It occurs usually associated with oil, and is probably produced by distillation from oil or coal within the earth. The wells are commonly several thousand feet deep.

Natural gas is superior to artificial gas in that it has a higher calorific value (about 1000 B.T.U. per cubic foot), it is much purer, and it is much cheaper unless it is necessary to pipe it for very long distances. About 5000 to 6000 cubic feet are used in the open-hearth per ton of steel produced. Preheating of natural gas for the open-hearth furnace is often omitted, the gas being introduced directly into the ports of the furnace.

448. Producer Gas. Only one form of artificial gas is of any importance in steel-making, this one being producer gas.

The modern type of gas producer is a cylindrical shell of steel, lined with firebrick. A common type of producer is shown by Fig. 220. Coal is charged into the hopper at the top and the cover is closed before the bell is lowered to discharge the contents into the producer. A supply of air, insufficient for complete combustion of the coal, is admitted through openings in the wind-box below the grates, and also through the pipe in the center. A steam injector is used to draw in the air. The ash falls through the grates into the ash pit, which is filled with water into which the shell of the producer projects, thus forming a water-seal.

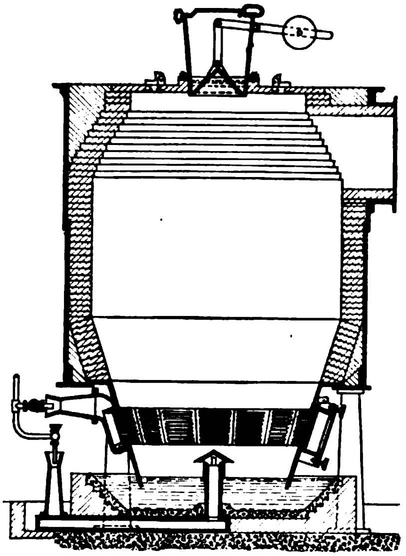


Fig. 220.—Water-sealed Gas Producer.

The air admitted through the grates of the producer converts a part of the carbon of the fuel to CO_2, which is reduced to CO in passing upward through the incandescent bed of fuel. The carbon monoxide is diluted by the nitrogen of the air introduced and somewhat enriched by the hydrogen of the decomposed steam and other moisture present. The actual ultimate composition of producer gas is variable, but averages about 61 per cent N, 20 to 25 per cent CO, 6 to 10 per cent H, 3 to 8 per cent CO_2, and 2 to 4 per cent methane.

One ton of average good bituminous coal yields about 150,000 cubic feet of gas whose thermal value averages about 130 B.T.U. per cubic foot. Therefore to produce 1 ton of steel, which calls for the development of from 5,000,000 to 6,000,000 British thermal units of heat, it is necessary to burn an average of from 570 to 700 pounds of coal in the producer.

The Basic Open-hearth Process

449. General. The basic open-hearth process, like the basic Bessemer process, differs from the acid process mainly in that it utilizes stock higher in phosphorus and sulphur, and a basic slag must be produced by the addition of strong bases to the charge in order to effect the removal of this excess phosphorus and sulphur. In order to resist the corrosive action of the basic slag the hearth must be lined with basic material as above described, but the hearth lining, whether acid or basic, plays no part in the purification of the iron.

450. The Furnace Charge. Operating Practice. Basic open-hearth practice is characterized by a number of quite distinct modifications, depending upon the choice of materials which constitute the furnace charge. The resulting processes are characterized as:

(*a*) The pig-and-ore process;
(*b*) The pig-and-scrap process, and
(*c*) The all-scrap process.

The pig iron used must contain from 1 to 2½ per cent P, less than 1 per cent of silicon, and at least 1 per cent of manganese. The carbon will usually run from 2.5 to 3.5 per cent. The pig iron may be charged either solid or molten, one form being used about as often as the other in American practice.

The substitution of scrap iron for pig iron results in shortening the time required for the operation, since there will be a lower percentage content of impurities to eliminate. When the pig iron is entirely replaced by scrap in the "all-scrap process," there is insufficient reducing material present to prevent excessive oxidation of the iron in melting, and it becomes necessary to use some form of carbon to supply the need for a reducing agent.

In the "pig-and-ore process" the charge is principally pig iron, to which ore is added in order to hasten the process. The limiting amount of ore is reached when the boiling of the charge becomes excessive. Unless pig iron is cheaper than scrap, the pig-and-ore process is not a commercially practicable one. Molten pig iron is sometimes used in this process, the iron being poured in on the ore, which has first been charged.

A mixer is commonly interposed between blast furnace and steel furnace as in the Bessemer process.

The "pig-and-scrap" process is now the most usual process, the average practice being to use about 50 per cent of each material, the exact proportions used in a given case being largely a question of relative costs. Very commonly a small proportion of ore or mill scale is added to hasten the process.

The order of charging varies, but the usual method consists in charging first a small quantity of small scrap to protect the hearth, after which the lime flux and the ore or mill scale is charged upon the scrap. Most of the balance of the scrap and about one-third of the pig is now charged and the furnace started. The balance of the scrap and the pig are added after an hour or two, when the former charge has melted down to make room.

The flux used is commonly lime, the amount required being dependent upon the contents of phosphorus, and especially sulphur, in the charge. High silicon also increases the amount of lime required in order to render the slag basic. In general the charge of lime amounts to from 10 to 30 per cent of the total charge, and the resulting slag contains from 35 to 45 per cent of CaO.

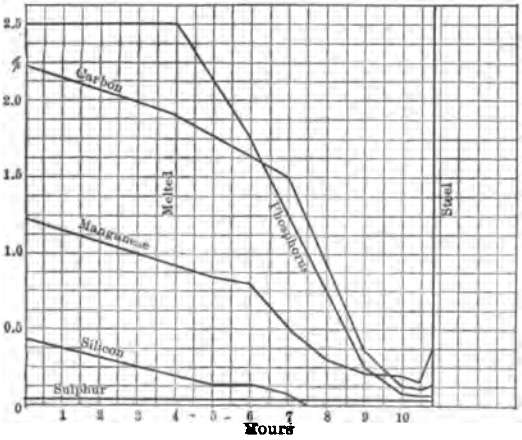


FIG. 221.—Removal of Impurities in Basic Open-hearth. (Bradley Stoughton.)

451. Chemistry of Basic Process. Melting on the basic hearth is attended by oxidation of the metalloids, the most easily oxidized ones being eliminated first. The general sequence of removals of metalloids is shown in Fig. 221.* The silicon, manganese and carbon are all considerably reduced in amount during the period of melting (the first four or five hours). The phosphorus, however, remains practically unaffected until the end of this period, when it begins to be rapidly oxidized.

It is necessary, in order to prevent the bath from becoming too cool and to prevent oxidation of the iron toward the end of the opera-

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* Bradley Stoughton, loc. cit., p. 133.

tion, to see to it that the carbon is eliminated last. If the carbon is disappearing too early it is therefore the practice of the melter to add pig iron to provide additional carbon. Sometimes, when the phosphorus burns out rapidly, and the carbon too slowly, it is necessary to hasten the oxidation of carbon by adding ore. The progress of the operation is tested from time to time by ladling out a small amount of metal, casting a small test billet, breaking it, and examining the fracture. Billet tests are now commonly supplemented by chemical analysis of frequent samples.

The slag performs several very important offices in the operation of the basic hearth. Its chief function is to take up and retain the oxides of the metalloids—silicon, manganese, phosphorus, and sulphur. It must also act as a protection to the bath from excessive oxidation by the furnace gases, and, by virtue of its contained oxides, assist in the oxidation of the impurities. For efficient action as a deoxidizing agent it must be very fluid in order that it may mix intimately with the bath.

The slag must also be rich in bases in order to retain the oxides of phosphorus and sulphur, and the removal of sulphur is greatly facilitated if the slag is rendered still more strongly basic by the addition of calcium fluoride just before the end of the operation. No oxides, such as ore or scale, can be added toward the end of the operation, lest the final slag be an oxidizing one, resulting in the metal being full of oxides and therefore turbulent when poured and very unsound after solidification.

452. Recarburization. Recarburization of basic steel cannot be accomplished in the furnace because the carbon, silicon, and manganese of the recarburizer would reduce the phosphorus in the slag and restore it to the metal.

On this account the recarburizer, in the form of ferro-manganese, together with coal, charcoal, or coke, is added to the stream of metal as it flows into the ladle. Provision is made for the removal of the greater part of the slag by overflowing at the top of the ladle. Spiegeleisen is not used as a recarburizer, because it must be used in a molten state and a cupola could not be operated to supply it in proper condition at the infrequent intervals at which a recarburizer is required in open-hearth operation.

Low-carbon steel is always poured only after the carbon has been reduced to about 0.10 or 0.15 per cent, the additional carbon required being added by the recarburizer. High-carbon steel is preferably handled in the same way, but it is cheaper and takes less time simply to reduce the amount of carbon slightly below the desired point, and then recarburize. The latter method is often used, but entails the danger of pouring steel while it is still too high in phosphorus and in oxides which cause unsoundness of the ingots.

453. Pouring the Ignots. The steel is discharged from the pouring spout or tap-hole of the furnace into a teeming ladle or fore-hearth, from which it is teemed into ingot molds mounted on cars as in the usual Bessemer practice above described. The ordinary open-hearth ingot may weigh as much as 10 tons and is therefore much larger than the usual Bessemer ingot.

THE ACID OPEN-HEARTH PROCESS

454. General. The acid open-hearth process differs from the basic open-hearth process principally in the character of the iron used, the omission of the flux, and the time required for the operation. Since the slag formed is acid, it is unable to retain oxides of phosphorus and sulphur, and a pig low in these elements is required. An acid lining of the hearth is of course required to prevent rapid corrosion by the acid slag. The time required for the operation is shorter than that for the basic process because the iron contains less impurities to be removed (especially because a larger proportion of scrap is used), because the process need not be prolonged to remove phosphorus, and because no part of the heat is consumed in melting and accomplishing the function of the flux.

455. The Furnace Charge. The charge of the acid furnace usually consists of approximately one-third pig iron and two-thirds scrap. The pig iron is fairly low in silicon, and low in manganese, phosphorus, and sulphur. The usual limits of composition are from 0.8 to 2.0 per cent silicon, 0.3 to 0.5 per cent manganese, and less than 0.05 per cent of both phosphorus and sulphur. The carbon content will be from 3.0 to 4.0 per cent.

The scrap will be of variable composition, but will average about 0.2 to 0.3 per cent carbon, 0.1 to 0.3 per cent silicon, 0.4 to 0.8 per cent manganese, and less than 0.05 per cent of both phosphorus and sulphur.

Ore is not usually initially charged in the acid furnace, but may be added during the process for the sake of increasing the oxidizing agencies to hasten the removal of carbon. The pig iron is charged into the furnace before the scrap in order to prevent the scorification of the hearth, which would occur if scrap were charged first.

456. Chemistry of Acid Process. The melting operation is in the main an oxidizing action, though the flame may be a comparatively reducing one during charging in order to prevent excessive oxidation of the pig iron and, more particularly, the scrap during this stage. (The reducing flame is secured by cutting down the air supply below the quantity required for complete combustion.)

The metalloids are largely eliminated during the melting-down stage, which requires some three or four hours, the silicon usually disappearing first, closely followed by the manganese. The amount of carbon oxidized during melting is dependent largely upon the amounts of the more easily oxidized elements (silicon and manganese) present. The lower the content of the latter elements, the greater will be the proportion of carbon oxidized. In any event two-thirds of the carbon will be removed very soon after the charge is altogether melted. The balance will be oxidized only very slowly, its disappearance usually being accelerated by the addition of ore to the bath. The slag in the acid process never constitutes the important oxidizing agency that it does in the basic process. The sequence of removals of the metalloids in a typical acid heat is shown by Fig. 222.

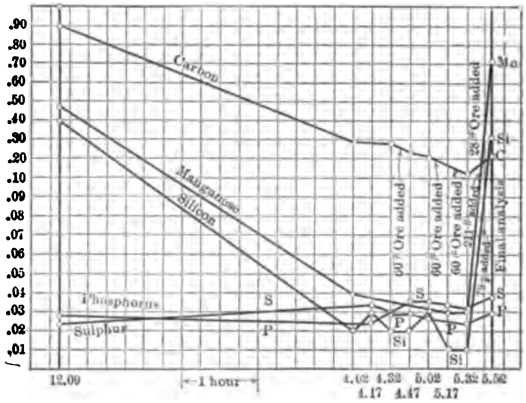


Fig. 222.—Removal of Impurities in Acid Open-hearth. (Bradley Stoughton.)

457. Recarburizing. Recarburizing in the acid process is accomplished in the furnace, rather than in the ladle, because the considerations which prevent recarburization in the basic furnace are not here operative. The practice as to the degree of recarburization varies, but in general the carbon is reduced to the practical minimum in the case of mild or medium steel, and the recarburizer added twenty to forty minutes before the heat is tapped. In the case of melting for high-carbon steel the carbon is usually reduced only slightly below the desired amount before the recarburizer is added. In this event, indeed, the addition to the bath is rather more a deoxidizer than a recarburizer, the primary object being the restoration to the bath of iron which has become oxidized. The recarburizer or deoxidizer is, in this process, ferro-manganese and ferro-silicon, as a rule. Coal is sometimes added in the ladle as in the basic process. The addition of the recarburizer necessarily largely increases the content of silicon and manganese in the steel, as well as the carbon content.

SPECIAL OPEN-HEARTH PROCESSES

458. Duplex Processes. There are two methods by which the acid Bessemer and the basic open-hearth processes may be combined in a so-called "duplex process," whereby the silicon, manganese, and part of the carbon are eliminated in the converter, the phosphorus and the remainder of the carbon being removed in the open-hearth.

In the most generally used duplex process the pig iron is blown in the acid converter until the silicon and manganese are practically eliminated and the carbon reduced to about 1 per cent, after which the converter charge is transferred to a mixer and thence to the basic open-hearth, wherein the phosphorus and the remainder of the carbon are removed.

The second method differs from the one just mentioned in that the Bessemer blow is continued till the carbon is reduced to only a few tenths of 1 per cent, after which the product is transferred to the open-hearth, mixed with a large proportion of pig, generally molten, and the process completed exactly as in the case of the latter part of the ordinary pig-and-scrap process.

The advantage of the duplex process over the Bessemer process lies in the fact that lower grade, high-phosphorus pig iron may be used and yet produce an open-hearth steel which is admittedly superior in quality to Bessemer steel, and which commands a higher price in the market.

The advantages of the combined process over the open-hearth process are the saving of about one-half of the time ordinarily required in the open-hearth, and the saving effected in cost of renewals of the hearth lining, because of the fact that the silica is removed before the metal enters the hearth. Forty to fifty heats per week are made in the duplex process, as compared with the eighteen heats usually made by the ordinary method.

459. The Talbot Process. The Monell Process. The Talbot process is a modification of the basic open-hearth process, whereby the hearth is worked continuously. The tilting furnace must be used, and the depth of bath is twice that ordinarily employed. The capacity of the furnace may exceed 200 tons.

The furnace is charged and conducted in the usual manner for the pig-and-ore process (no scrap being used), until the carbon is reduced to the desired point. The slag is then poured off and about one-third of the steel is poured into the ladle, recarburized, and teemed. Iron ore and limestone are now added to the bath to form a new slag, and molten pig iron is poured in to make the charge equal to its original amount. Oxidation proceeds very rapidly, owing to the large amounts of iron oxide in the slag. The interval between the addition of pig and the pouring of steel is only from three to six hours, and three to four heats are poured per day.

The principal advantages of the process are the large tonnage produced and the excellent temperature control possible. The furnace is expensive, however, both to build and to maintain.

The Monell process is another modification of the basic open-hearth process, wherein a very strongly oxidizing slag is prepared before molten pig iron is charged. The slag is produced by melting limestone with ore or other iron oxide equal to about one-fourth of the pig-iron charge. Molten pig iron is poured into this slag and oxidation proceeds with extreme rapidity, most of the silicon, manganese, and phosphorus being eliminated within one hour. The balance of the process is exactly similar to the ordinary pig-and-scrap process, and the total time required is about the same.

ELECTRIC REFINING OF STEEL

460. Electric Refining Processes in General. The part which electricity plays in the various electric steel processes is, as in the case of the electric reduction of ores, simply that of a source of heat. Slags, which are strongly oxidizing in character, must be added to the bath in order to effect any refinement. In practice, the slag used is a strongly basic iron-oxide slag, because such a slag will oxidize phosphorus as well as retain the oxide formed. If much phosphorus is to be removed, or if it is to be reduced to a very low point, it is necessary to use two slags, skimming off the first after it becomes highly phosphorized.

Sulphur can be reduced only by removing the iron-oxide slag, after the elimination of phosphorus, and producing a slag that is made up almost entirely of lime. The presence of manganese favors the removal of sulphur, because manganese sulphide is more readily taken up by the slag than iron sulphide, thus making possible the formation of calcium sulphide, in which form the sulphur is retained in the slag.

One of the greatest advantages of electric refining processes lies in the fact that dissolved gases, occluded oxides, etc., are readily removed from the steel through the agency of heat alone. The lack of perturbation of the bath and the length of the process, combined with the very high temperature attained, provide ideal conditions for the slow migration of these very small particles to the surface. No subsequent deoxidation of the metal is required after finishing.

The general nature of the processes of electric refining, as carried out in the various types of furnaces, will be briefly indicated in the discussion of furnaces which follows:

461. Types of Electric Refining Furnaces. Three quite distinct types of electric steel refining furnaces have been developed to the point of practical commercial application. These are:

(1) Furnaces employing an open arc between electrodes above the bath, the latter being heated by radiation alone. The Stassano furnace is of this type.

(2) Furnaces employing an arc between electrodes and the bath, the latter forming a part of the electric circuit. The metal is heated largely by conduction from the slag bath, which carries much of the current and is heated both by radiation and by reason of its electrical resistance. The Héroult, the Girod, and the Keller furnaces are of this type.

(3) Electric induction furnaces, wherein the bath forms the secondary of a transformer consisting of a closed circuit with but a single turn. The Kjellin and Röchling-Rodenhauser furnaces are of this type.

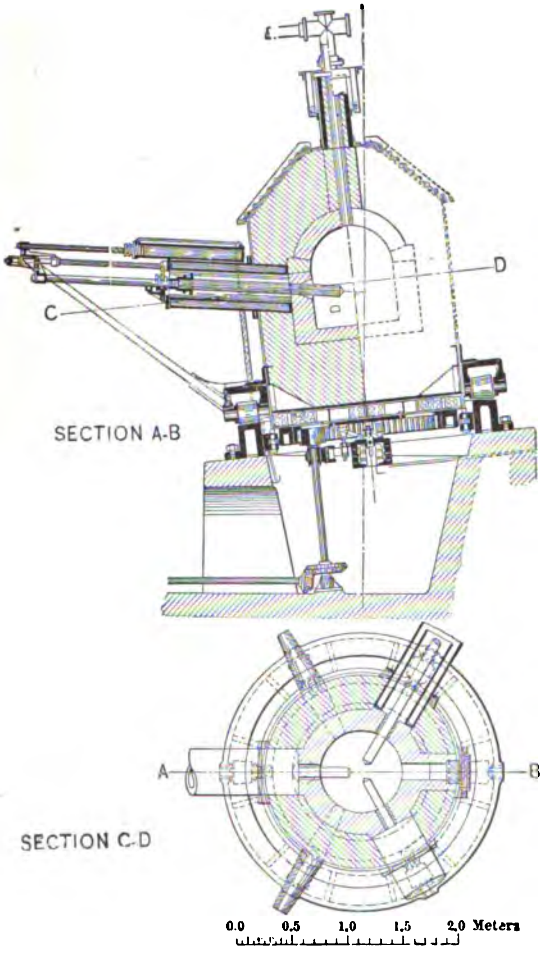


Fig. 223.—Stassano Open-arc Electric Furnace.

462. Open-arc Furnaces. The Stassano Furnace. The Stassano furnace is the best-known type of open electric-arc furnace. Its general arrangement is shown by Figs. 223*a* and 223*b*. The working chamber is a cylindrical structure, lined with basic refractory brick, mounted upon a circular track at a slight inclination from the vertical, and slowly rotated in order to increase the mixing effect.

Electric energy is converted into heat through the medium of an arc between carbon electrodes just above the level of the bath, the bath being heated by radiation. Three-phase alternating current is used, three electrodes being necessary. The power consumption is about 1000 kilowatt hours per ton of steel produced from cold scrap. Any grade of scrap or pig may be used, and the refining carried to any desired degree, the steel produced being comparable to best crucible tool steel in quality. The maximum capacity of the Stassano furnace is about 5 or 6 tons of metal per heat.

463. Arc-resistance Furnaces. The Héroult, Girod, and Keller Furnaces. The Héroult electric furnace resembles closely the open-hearth furnace except that heat is supplied by electrical means instead of by the combustion of gas fuel. The form of the furnace is shown by Figs. 224*a* and 224*b*.

Current enters through one of the electrodes which are suspended above the bath, arcs to the charge through which it passes, and thence arcs to the negative electrode.

The Héroult furnace may be used to refine any grade of scrap, but its most important applications have been in conjunction with Bessemer converters and with the open-hearth in duplex units. The metal is, in this case, brought in a molten state from the converter or from the open-hearth, and practically any desired grade of steel may be produced. Superior grades of rail steel, axle steel, steel for wire, steel for castings, tool steels, and special alloy steels have been made with great success by refining either Bessemer or open-hearth metal in the Héroult furnace.

The capacity of the largest Héroult furnaces is about 15 tons of metal, and the refining of Bessemer metal has been carried on for weeks at the rate of twelve to fifteen heats per day, meaning a daily output of about 180 tons of super-refined steel. The power consumption in refining molten Bessemer metal is from 100 to 200 kilowatt hours per ton of steel, while in melting and refining cold scrap the power consumed is 600 to 800 kilowatt hours per ton. Three-phase alternating current is used.

The Girod electric furnace, Figs. 225*a* and 225*b*, like the Héroult furnace, employs an arc between the positive electrode and the bath, but the current is conveyed away by conductors built in the magnesite lining of the bottom of the hearth, instead of arcing to a negative electrode above the bath. The negative pole is formed by a number of pieces of soft steel which are prevented from fusing to too great a depth by water cooling.

The Girod furnace has been used abroad for practically the same purposes as the Héroult furnace has been used in this country. It works well as a duplex unit with the Bessemer or open-hearth and is also very

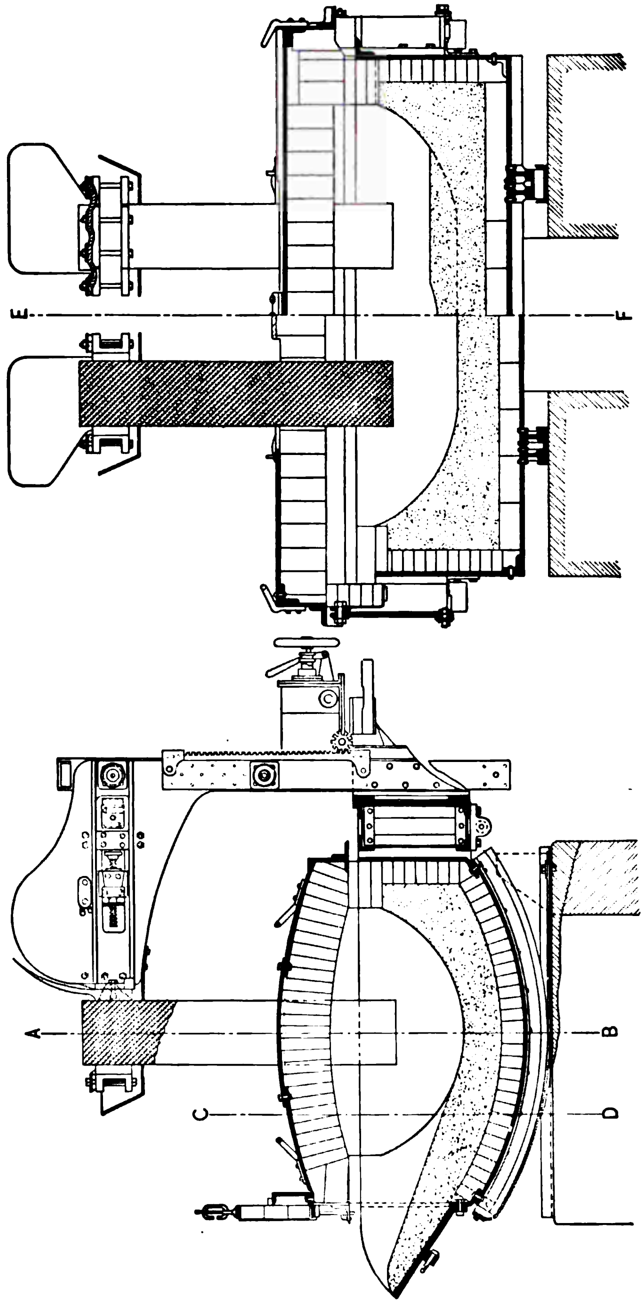


Fig. 224.—Héroult Arc-resistance Electric Furnace.

efficient in melting and refining cold scrap. Its power consumption and capacity is about the same as the Héroult, except that the largest furnaces have a capacity not exceeding 8 to 12 tons.

The Keller electric furnace, Fig. 226, resembles the Girod furnace in having a conducting bottom, but instead of having only six negative pole pieces, iron bars 1 to 1½ inches in diameter are placed vertically over the entire bottom, being spaced only about 1 inch apart. The intermediate spaces are rammed tightly with magnesia. After becoming heated up the entire bottom becomes a conductor, the magnesia itself becoming conductive. It is claimed for such a bottom that the more uniform distribution of energy flow means added efficiency as compared with the Girod furnace, and that the bottom is more durable.

It is evident that with both the Girod and the Keller furnace the current density or amperage must be double that required for a furnace like the Héroult, where the electrodes are in series, the bottom not being one of the poles.

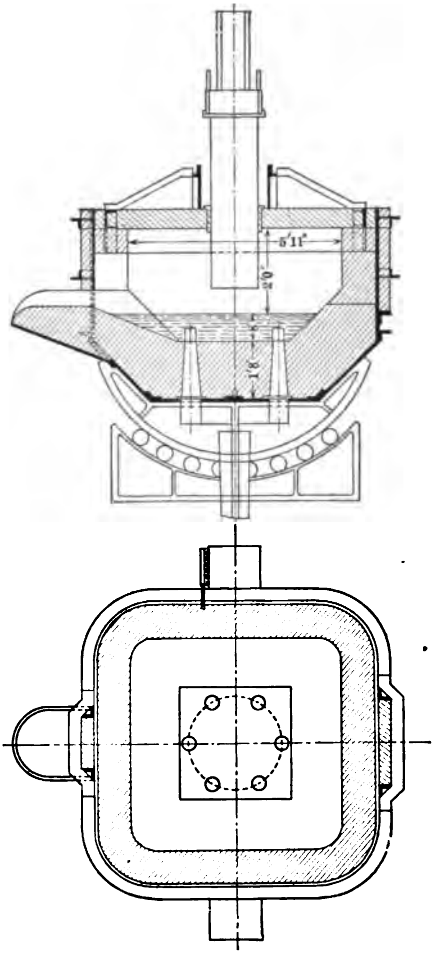


Fig. 225.—Girod Arc-resistance Electric Furnace.

464. Induction Furnaces. The Kjellin and Röchling-Rodenhauser Furnaces. The electric induction furnace differs radically in theory and design from the furnaces employing electrodes. The induction furnace is in principle simply a stepdown transformer, wherein the metal under treatment forms a closed secondary circuit.

One of the simplest forms of induction furnace is the Kjellin furnace shown in Figs. 227*a* and 227*b*. The primary coil, through which high-voltage alternating current is passed, is shown at *AA*; the magnetic core of laminated iron, in which an alternating current is induced by the primary, is shown at *BB*; and the bath of metal under treatment shown at *CC* (contained in the circular crucible *DD*, built of calcined magnesia or dolomite) forms the secondary in which current is induced by the magnetic core. The resistance offered by the molten metal to the passage of the induced current is the source of heat whereby any desired degree of refinement may be accomplished.

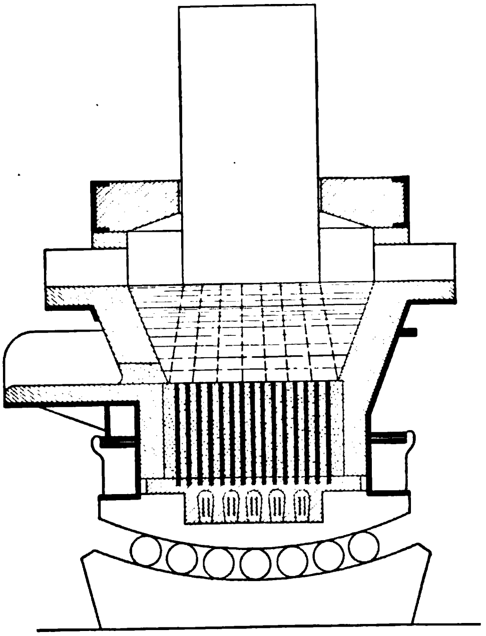
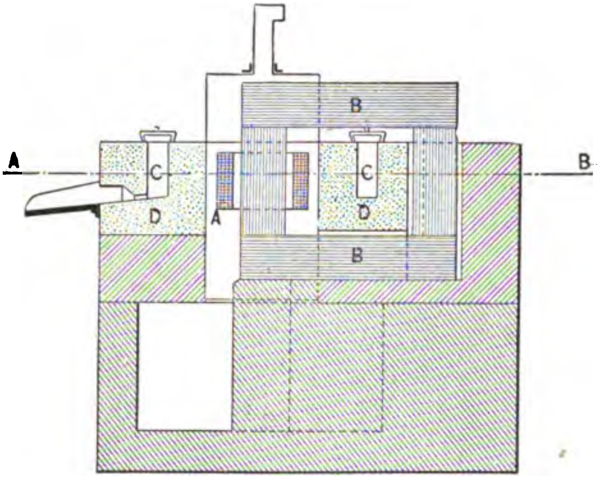


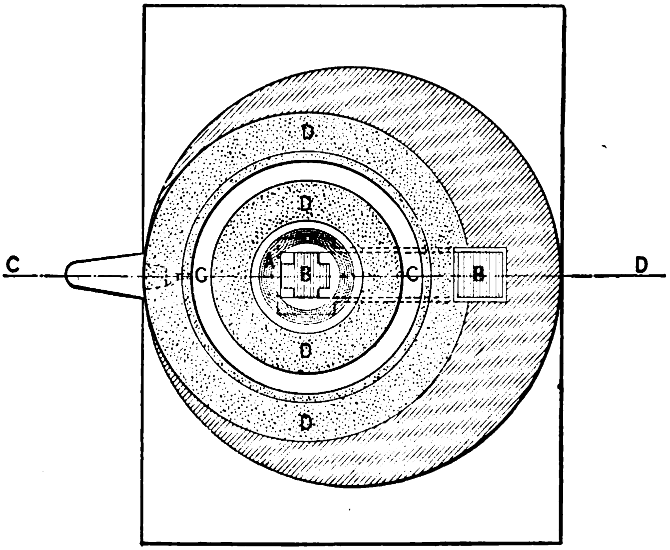
FIG. 226.—Keller Arc-resistance Electric Furnace.

This furnace ranks high as to thermal efficiency, but its use is limited to rather small capacities because of the limited contact area between slag and metal, which means slow refining. Few furnaces of this type have been built with capacities exceeding ½ ton, and its principal application has been in the refinement of metal for tool steel. If the metal charged is not already molten, a portion of each charge must be left in the crucible to establish a complete circuit until the solid metal has been melted down.

The Röchling-Rodenhauser furnace, shown in horizontal section in Fig. 228, does not differ in principle from the Kjellin furnace, being in fact simply a combination of three simple induction furnaces designed to use three-phase current. There are three primary coils, *AAA*, the cores of which, *BBB*, are connected together above and below by a horseshoe-shaped member built of laminated iron. The adjacent portions of the annular cavities, *CCC*, containing the bath, widen and join to form a central open chamber, *D*, which serves as a working chamber, upon which slags, ores, alloys, etc., may be charged and manipulated. This central chamber greatly increases the expedition with which refinement is accomplished. In order to prevent loss through magnetic leakage from the primary coils a few turns of heavy copper wire are placed outside these coils and connected with steel plates, *EEE*, embedded in the masonry of the lining. The refractory material covering these plates



SECTION C-D



SECTION A-B

0 0.5 1.0 1.5 2.0 Meter.

FIG. 227.—Kjellin Electric Induction Furnace.

is of such a nature that it acquires electrical conductivity when heated, thus allowing the current which flows to the terminals to pass directly to the bath.

The usual capacity of the Röchling-Rodenhauser furnace does not exceed 2 or 3 tons; the power consumption is 200 to 250 kilowatt hours per ton (using molten charges), and the product may be super-refined mild steel, high-grade tool or alloy steel, steel castings, or even rail steel.

465. Applications and Limitations of Electric Furnaces and Electric Refining Processes. The electric furnace has already made itself a formidable rival of the crucible process, because it is able to make larger tonnages of tool steel of crucible quality at a lower cost. In the field of steel castings it has also a considerable advantage over the highest grade crucible-made castings in the matter of cost, though it cannot compete with the open-hearth in the production of lower-grade castings.

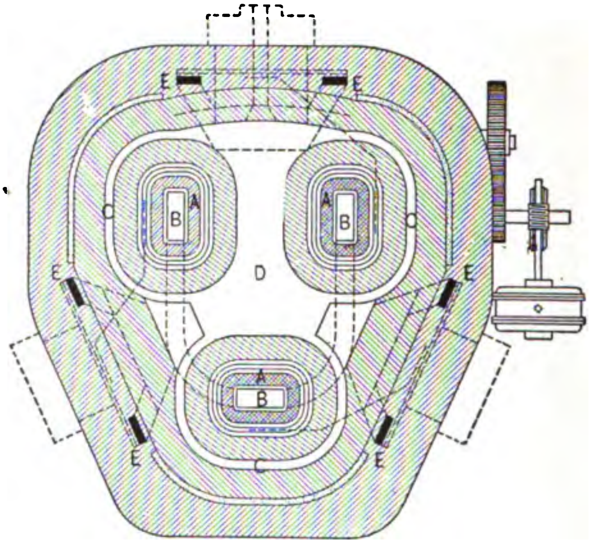


FIG. 228.—Rochling-Rodenhauser Electric Induction Furnace. Horizontal Section.

The electric furnace is not, and perhaps cannot under usual conditions be, a competitor of the Bessemer converter and the open-hearth in the production of mild and medium steel of ordinary quality. It has already become an important adjunct of both of these processes, however, taking their product and super-refining it to produce steel for special purposes, a notable one being the production of steel rails which, without sacrificing hardness, are much tougher than the ordinary Bessemer product.

In the production of special alloy steels, the electric furnace has a special advantage over other steel processes in that it need not be operated under oxidizing conditions, but may be worked under either neutral or actually reducing conditions. This is an important consideration in using certain valuable alloying elements which are very easily oxidized and lost in other furnaces.

ROLLING MILL OPERATIONS. THE FINISHING OF STEEL

Reheating

466. Necessity for Reheating. An ingot cannot be sent to a rolling mill and rolled immediately after the ingot mold has been removed, because at that time the interior is still molten. If, on the other hand, the ingot were allowed to stand until the interior has solidified, the exterior would be too cold to be worked. It is therefore necessary to place the ingots, immediately after stripping, in a furnace where the interior may be solidified and the exterior kept at the required temperature for working.

The process of rolling finished steel sections from ingots is a protracted operation, necessitating a great many passes of the metal through the rolls. It is therefore necessary, at one or more stages in the reduction of the section, to reheat the bloom or billet or slab which has been formed by the initial reduction of the ingot, and which has cooled below the proper working temperature.

Two classes of reheating furnaces are therefore a necessary part of the equipment of a rolling mill: first, a furnace for heating ingots, or at least equalizing their temperature within and without, and second, a furnace in direct connection with the rolling mill, wherein billets or unfinished shapes may be reheated at any stage in the process of rolling.

467. Reheating Furnaces. Practice of Reheating. There are three principal classes of reheating furnaces: (1) the "soaking pit" and (2) the regenerative gas-fired pit-furnace for ingots, and (3) continuous furnaces for billets and other small sections. Special types of reheating furnaces are also required for reheating large blooms and slabs.

The original soaking pit, which is still used abroad but has been replaced by the gas-fired pit-furnace in this country, is simply a masonry chamber, built below the floor level, and charged through the top in order that the ingots may remain vertical while solidifying. No fuel is employed, but the ingots are stripped and placed in the soaking pit as soon as possible after teeming, the heat of the still molten interior of the ingot being depended upon to bring the exterior to the proper temperature.

The regenerative gas-fired pit-furnace is also a vertical furnace, built below the floor level, and charged through the top. Gas fuel is burned within the heating chamber, the arrangement of the furnace being exactly similar to that of the regenerative gas-fired crucible furnace. (Fig. 204.)

Billet-heating furnaces are now commonly of the reverberatory type, gas-fired, and recuperative in principle. Such a furnace is shown in Fig. 229. The billets are charged at the cool end of the furnace, and are pushed along through the length of the furnace by an hydraulic ram mounted at the charging end. Water-cooled pipes laid in the bed of the heating chamber and extending throughout its length, provide a sort of track along which the billets are pushed. The billets encounter hotter temperatures as they approach the end where the gas and air ports are located, and are there discharged and conveyed back to the rolls. The burned gases, upon leaving the heating chamber, are caused to pass through a series of pipes in a chamber below the working chamber, and the air which is to be used for combustion is caused to circulate through this chamber, thus becoming preheated. (This explains the application of the term "recuperative" to the furnace). The gas need not be preheated since it comes to the furnace directly from a producer worked in direct connection with the furnace.

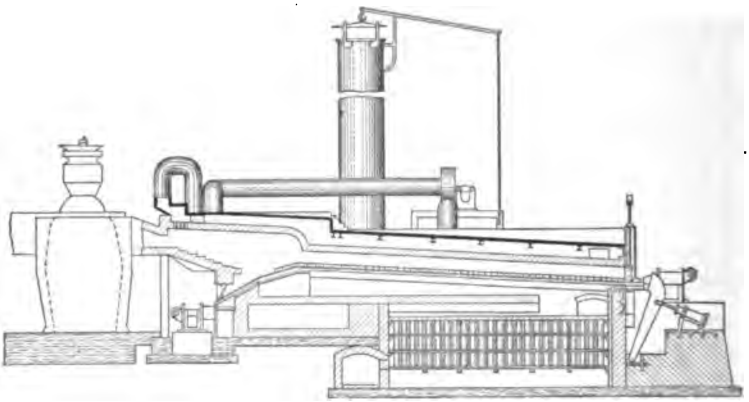


FIG. 229.—Gas-fired Recuperative Billet Heating Furnace.

Rolling

468. General. The reduction of metal in rolls is, from the standpoint of the possible beneficial effect of the mechanical work involved upon the structure and mechanical properties of the steel, inferior to either hammering or pressing. It is, however, by far the most rapid method, and this fact coupled with its lower cost and lesser demand for labor is responsible for the almost universal use of rolls wherever their use is not practically prohibited by special considerations affecting only certain shapes and classes of products.

The action of rolls not only compresses the metal in a direction along the radii of the rolls, but the traction force of the rolls in pulling the metal through causes longitudinal tension in the surface layers. In case the section is intricate, necessitating deep indentations in the rolls, the surface velocity is much less where the rolls are deeply cut than where the diameter is greater, thus tending to drag different parts of the section through at different speeds. This renders the distribution of the amount of working still less uniform and in extreme cases causes tearing of the metal.

Reduction can take place only in a vertical direction, but this reduction is always accompanied by a certain amount of expansion sidewise and a large amount of extension lengthwise. The amount of reduction in each " pass " through the rolls is extremely variable, running all the way from 5 to 50 per cent, but usually not averaging over about 15 per cent in each pass for such shapes as rails, structural sections, etc. The amount of extension lengthwise may be judged from the fact that a 3-ton ingot will produce two 90-pound rails each about 80 feet long, even after a considerable discard has been made to get rid of the pipe, etc.

The speed of rolling practiced is very great, some passes in rolling rails being made at as high a rate as 10 miles per hour, while rods are sometimes rolled at a rate of 30 miles per hour. (This speed is so great that rods will be heated by the distortion in rolling more rapidly than the heat can be radiated, and they are finished at a higher temperature than at the beginning of rolling.)

469. Rolling Mills. The most essential parts of a rolling mill are of course the rolls. Cast-iron rolls, which have been chilled to produce a hard exterior, and turned in a lathe to produce a smooth surface of the desired form, are very commonly used, especially for finishing rolls. High-carbon steel is also used when the rolls must be very strong, and even nickel-steel rolls have been used. All of the rolls except the ones used for finishing have their surface roughened in order to increase their grip on the metal.

Rolls are turned in an infinite variety of shapes, varying from the plain cylinders used for plates and some rectangular shapes to the rolls used for structural shapes, rails, corrugated bars, etc., which may be quite intricate in form. All rolls except plain cylindrical rolls make provision for several passes of the metal, each pass approximating the final form of the section desired more closely than the last.

Rolling mills may be in general classed under one of three heads: " two-high " mills, " three-high " mills, and " universal " mills.

Two-high mills consist of a single pair of rolls mounted in the same vertical plane. One variation of the two-high mill is the " pull-over " mill, whose rolls always run in the same direction, so that the metal after each pass must be pulled back over the top of the rolls to be fed in for the next pass. This is the simplest form of mill and the cheapest, but its operation is slow, and it is adapted only for rolling small shapes which can be readily handled. A more important type of two-high mill is the "reversing" mill, the rolls of which may be made to run in either direction by reversing the engines which drive them. Successive passes are therefore made in opposite directions through the rolls. The two-high reversing mill is often used in "cogging" ingots.

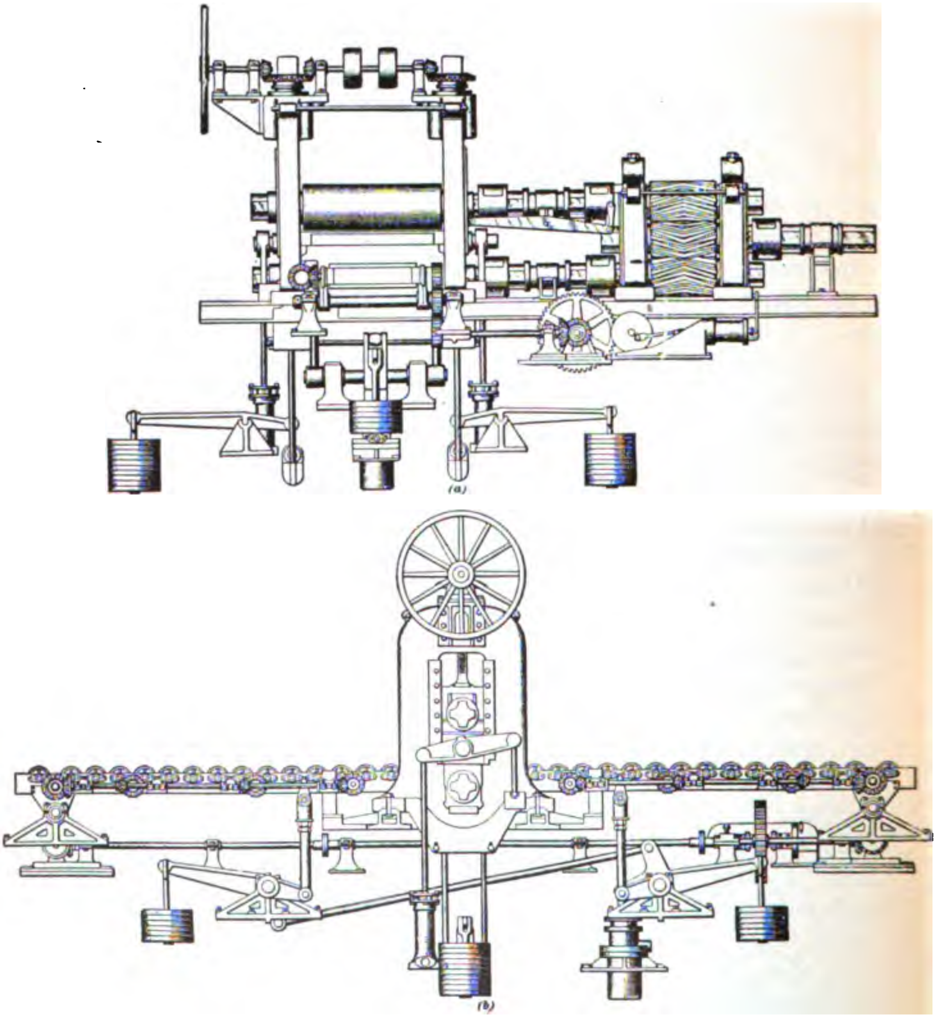


Fig. 230.—Three-high Plate Mill.

The *three-high mill* has three rolls geared together, so that the metal may make one pass between the lower and the middle roll, and the next pass in the opposite direction between the middle and upper roll, without reversing the rolls. A very large proportion of all steel shapes are rolled or at least finished by a three-high mill.

The *universal mill* is provided with two auxiliary rolls mounted vertically just in front of the horizontal rolls. The distance between the axis of these rolls is adjustable horizontally and they are designed simply to keep the edges of the metal smooth without effecting any reduction. Universal mills are made with vertical rolls on only one side of the horizontal rolls or on both sides, and they may be either two-high or three-high mills.

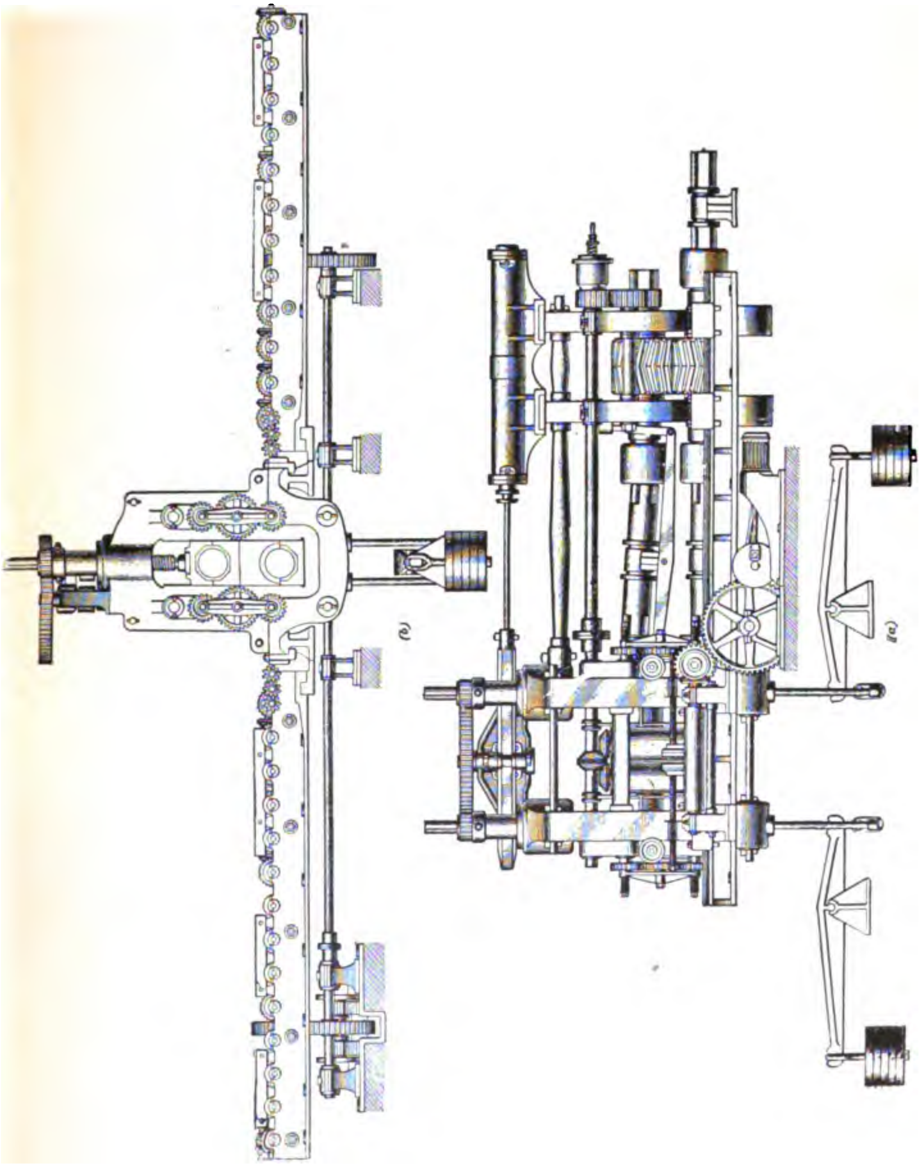


FIG. 231.—Two-high Universal Mill.

All rolling mills which handle anything except very light material must be provided with a series of rollers in front of and behind the rolls, known as the "roll tables." The roll tables for three-high mills must be capable of being raised or lowered at the end next the rolls, in order that the metal may be directed between either the upper or the lower set of rolls.

Two views of a three-high plate mill are shown in Fig. 230, and two views of a two-high universal mill in Fig. 231. The sketches of Figs. 232, 233, and 234 illustrate the application of three-high mills in the cogging of ingots and the rolling of special shapes.

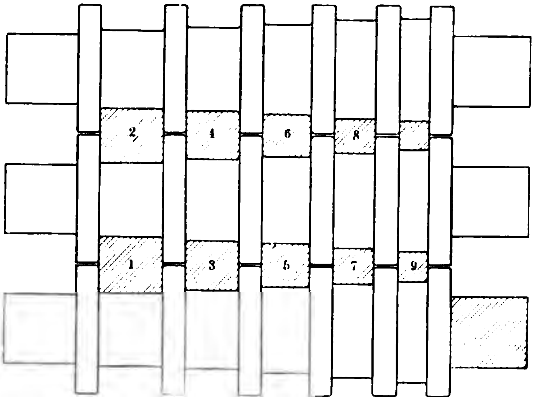


Fig. 232.—Cogging Rolls.

470. Examples of Rolling Practice. *Steel Rails* are rolled by a process whose general features are as follows:

The ingot, after reheating in a pit furnace, is cogged down to a bloom whose cross-sectional dimensions are about one-half those of the original ingot. This operation is accomplished by a series of about 8 or 10 passes through a set of cogging rolls whose form is that shown by Fig. 232. The bloom is now sheared at each end to remove the pipe and the ragged end formed by the rolls, cut in two in the center, returned to the reheating furnace, and brought again to the proper temperature for rolling. The next series of 4 to 6 passes are made in one or more trains of roughing rolls (Fig. 233), and the last 8 or 10 passes in a train of finishing rolls (Fig. 234). (The figures here given are merely representative of average practice. The number of passes in each roll train varies considerably in the different rail mills.)

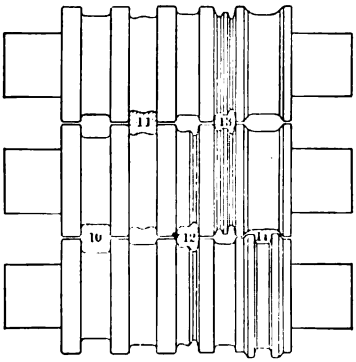


Fig. 233.—Roughing Rolls.

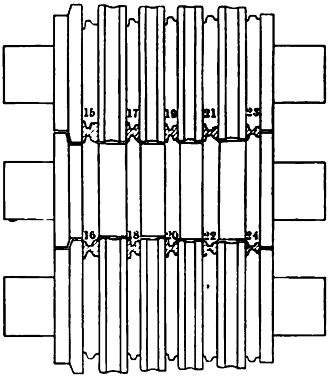


Fig. 234.—Finishing Rolls.

Structural Steel Sections are rolled in almost exactly the same manner as are rails. The different sectional areas for a given size of any structural shape such as angles, I-beams, channels, etc., may be produced with the same set of rolls by simply changing slightly the axial distance between the finishing rolls as indicated by Fig. 235.

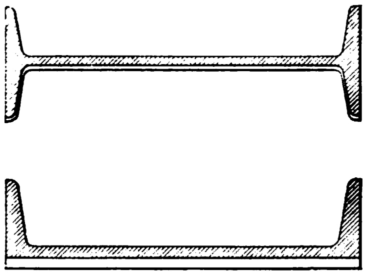


Fig. 235.—Method of Increasing Areas of Rolled Shapes.

Plates are cogged from the ingot in a mill similar to that shown in Fig. 231 except that the vertical rolls are not used. The resultant " slab " is sheared up into smaller slabs, the pipe discarded, and the slabs reheated before completing the rolling operation in a mill of the type shown by Fig. 230. The successive reduction in the thickness of the plate is accomplished by bringing the rolls slightly nearer together between passes. The surface is cleared of the scale and a smoother finish secured if salt or sand is thrown upon the plate from time to time. Such procedure results in carrying between the rolls some of the cooling water which is kept running on the rolls, and the formation of steam when the water is pressed on the hot plate causes sharp explosions which tend to clear the surface of the mill scale.

Rods are rolled in a manner similar to that described for steel rails except that the original bloom is usually cut up into a number of small sections before reheating and rolling. A mill called a " guide mill " is used, the material after each pass being bent around and guided into the next pass by a device specially attached to the mill for the purpose.

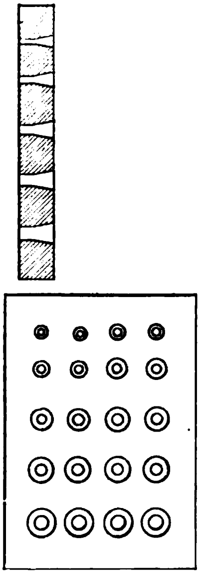


Fig. 236.
Draw-plate for Wire.

Wire-making is only a rolling operation so far as the making of the wire-rod is concerned. A considerable portion of the reduction of the section is accomplished by a special operation known as " cold-drawing." The wire rod is rolled in the manner above noted, its final diameter being usually from 1/4 to 1/2 inch. The wire rod is then wound into coils and pickled in a dilute solution of sulphuric acid, which removes the scale. Water is next sprayed on to wash off the acid, and this is followed by immersion in a bath of lime-water, which removes the last traces of acid. The coils are now dried in an oven and sent to the wire-drawing mill.

Cold drawing consists in successively reducing the section, and extending the length, by repeatedly pulling it cold through tapered holes in a die or " draw-plate " (Fig. 236). Each hole through which the metal is drawn is somewhat smaller than the preceding hole, the average amount of reduction being from 20 to 25 per cent. Some thick lubricant is applied to the draw-plate to reduce friction and prevent too rapid wear on the hole.

Drawing is performed on " draw-benches " which comprise a frame upon which the draw-plate is mounted and a reel which is driven by power and serves to pull the wire through the plate and coil it up. Often several plates are mounted on one bench, the holes in each being smaller than those in the preceding one. In this case a power reel must be placed between each pair of holes, around which the wire is given a few turns, since the strength of the wire after passing the last plate would not suffice to pull it through several holes. The wire must be annealed by heating to a low red heat in a closed receptacle after each 3 to 10 passes, because of the hardening of the metal caused by drawing. The finished wire is also annealed unless it is to be sold as hard-drawn wire.

Wire is often galvanized by drawing it first through a weak pickling solution to remove the scale, through a rinsing bath, and then through a bath of molten zinc. The excess of zinc is removed by drawing the coated wire through asbestos plugs.

Iron wire is made from wrought-iron billets in exactly the same manner as steel wire, except that the production may be accomplished in fewer passes and with less difficulty caused by hardening.

Plow-steel wire is simply a high grade, high-carbon wire, made from crucible steel. It is so called because it was originally used for dragging steam plows.

Lap-welded Pipes are made by the method indicated by Fig. 237. The metal is first rolled into flat strips called "skelp," of the desired thickness, then bent to a U-shaped section and, by another pass, to a circular section with the edges overlapping. (Small pipe may be bent to the circular section by drawing the skelp through a die.) The metal is now brought to a welding heat and is passed through a pair of welding rolls over a "mandrel" which is supported between the rolls on the end of a long rod. A second pass through "sizing" rolls is made to insure accuracy of size.

Butt-welded Pipes are made by drawing the skelp at a welding heat through a die or "bell" (Fig. 238), which welds the edges together without lapping

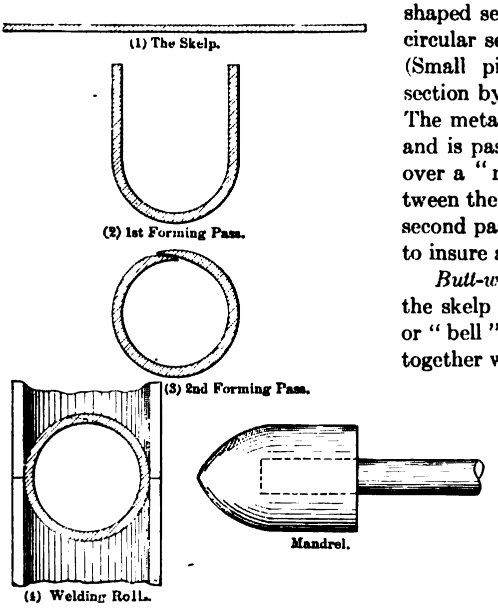


Fig. 237.
Making Lap-welded Pipe.

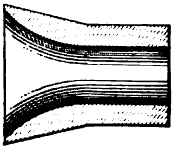


Fig. 238.
Bell for Making Butt-welded Pipe.

Seamless Tubes (small sizes only) are made either by forcing a flat plate through a cylindrical die by means of a mandrel, or by piercing a billet longitudinally, expanding the hole by forcing larger and larger tapered expanders through it, and finally rolling over mandrels until the section desired is attained.

Cold-rolled Steel is steel the last pass of which through the rolls is made with comparatively cold metal. Pickling is necessary before cold rolling to remove the scale, and the result is a great gain in accuracy in size and form, and in surface finish. The strength and elastic properties are also greatly improved by cold rolling.

Finishing Steel by Steam Hammer and by Presses

471. Forging under the Steam Hammer. In the early days of the steel industry the steam hammer or its predecessor, the helve, was the principal means whereby steel ingots were worked up into the desired final form; but as ingots became larger and heavier, the hammer was to a great extent replaced by rolls which, although they do not work the metal so well, are much more rapid in operation and involve less expense for labor and for reheating.

In working metals under the hammer the pressure of the blow acts for only a very short interval and the metal recovers somewhat from the effect. This results in the deformation produced not being in proportion to the instantaneous force applied, and the process is therefore slow. For small sections, however, and for the exterior portion of larger sections, the metal is worked better than by any other method of reduction, resulting in the refining of the grain of the metal by decreasing the size of the crystals, and improving the quality of the metal in every respect. For thick sections a very heavy blow would be required to properly work the metal all the way to the center, but this means a very heavy hammer and very expensive foundations for the anvil. The practical limit of size is now considered to be not heavier than 50 tons, and few hammers are now built with capacities beyond 30 tons. For all heavier forging work the hydraulic press is preferred.

The steam hammer now finds little application in the steel industry except in the forging of high-grade crucible or cement steel (where the value of the product and the especial desirability of giving the metal the fine grain attained by hammering justifies the higher cost), and in the production of that large class of articles called " drop-forgings," whose form is too intricate for rolling but which are subjected to conditions in service too severe to be met by iron castings or even steel castings. This class of articles includes a great variety of machine parts, small tools, automobile parts, etc.

Drop-forgings are made by the use of dies, between which the metal is worked into the desired form by the blows of a steam hammer. The dies are made of hardened steel, the impressions formed in the faces of the dies corresponding to the impressions formed in the mold for a casting. The metal is placed upon the lower die, which is made fast to the anvil, and the upper die is carried by the head of the hammer. Very often a series of dies are necessary to complete a forging, each set approximating more closely the final form required.

The stages in making a simple drop-forging are indicated in Fig. 239. The metal, in the shape of a bar of steel, is first upset to gain metal for the larger end of the forging and is then placed in the die (*a*), which roughly approximates the desired form. The partly formed piece is shown at (*a*′) after removal from die (*a*). It is now transferred to the second die (*b*) which completes the shaping of the piece but leaves a " fin " all around, shown at (*b*′). This fin is removed by shearing in the die or punch (*c*), the forging being withdrawn through the slot below the die. It now appears as shown at (*c*′). The tool is now cut off from the bar, and is finished by grinding upon an emery wheel.

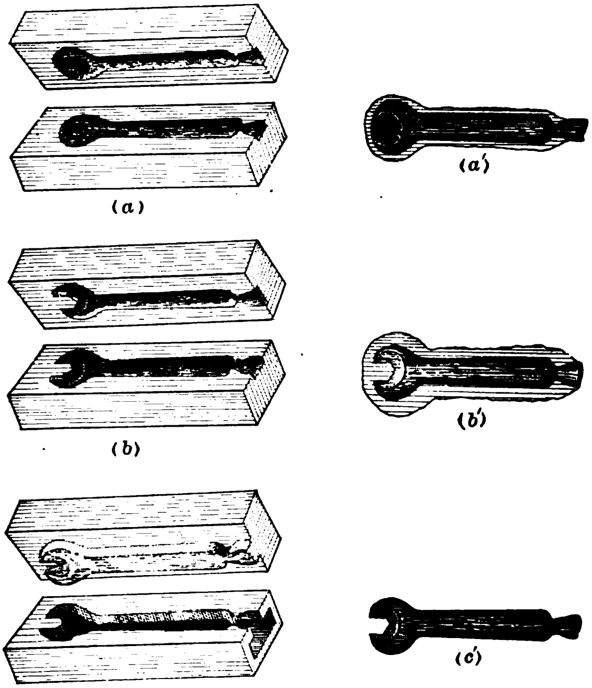


Fig. 239.—Stages in Making a Drop-forging.

The majority of all drop-forgings for machine parts, etc., are not forged to the exact size required, but an allowance is made for machining. This results not only in securing a better finish, but the removal of the exterior coat of scale may reveal the presence of flaws which have been hidden.

472. Forging by Means of Presses. The effect of pressing steel, by the action of large hydraulic presses, differs from that produced by the action of a hammer, in that the force applied acts for an appreciable interval of time, and the distortion produced extends deeper into the metal.

In consequence, the press produces a better crystalline structure than does the hammer for all except very thin sections, and is therefore used in preference to the hammer for all heavy forging. The press is able to do more work with the same power expenditure than is the steam-hammer, but cannot compete with rolls except where the superior working of the metal secured by pressing is more important than relative costs.

The hydraulic press consists essentially of a hydraulic cylinder in which a plunger or ram moves vertically, and which is forced down upon the metal supported on an anvil block or bed as in the case of hammers. Presses vary in size from a few tons capacity up to 14,000-ton armor-plate presses which will handle ingots weighing 50 tons or more. Fig. 240 is a view of an hydraulic press forging a 15,000-pound ingot. The appliances whereby the ingots are moved forward and turned under the ram are shown.

FIG. 240.—Hydraulic Press Forging Ingot.

In addition to their use in the reduction of ingots in place of a cogging mill, and in the pressing of heavy plates, hydraulic presses are largely used in the production of forgings pressed between dies, as in the case of the steam hammer, and also in the production of a large class of articles made of thin plate steel which is pressed cold between dies. A press used for the latter class of uses is called a "flanging press."

DEFECTS IN INGOTS AND THEIR CORRECTION

473. Blow-holes, Piping, Ingotism, and Segregation. One of the greatest sources of trouble for the steel-maker is the occurrence of *blow-holes,* which are almost unavoidably formed in some degree while the metal is solidifying in the ingot mold. Blow-holes are caused by the presence of gases such as hydrogen, nitrogen, and oxygen which are held in solution by the metal when molten but released as the metal solidifies, and they are also caused by the presence in the metal of iron oxide, which upon encountering carbon, forms CO gas.

The gas in blow-holes is usually reducing in effect and therefore the surfaces of the holes do not become oxidized and will weld together when the ingot is subjected to pressure in the operation of rolling or pressing. Blow-holes near the surface of an ingot, however, are apt to break through to the exterior, allowing oxidation and preventing perfect welding in the rolls.

Another defect in ingots, which cannot be corrected in rolling, is the occurrence of the *pipe* or shrinkage cavity which forms during solidification. Since the metal cools first in contact with the walls of the mold, the interior will remain molten after an outside solid shell has formed. The interior metal contracts as it solidifies progressively from the outside inward, causing the formation of a cavity which becomes filled with gases evolved during solidification. Since the hottest metal is at the top of the ingot, the upper portion remains molten longer and acts as a feeder to fill the shrinkage cavity in the bottom portion. The pipe is thus localized in the upper third of the ingot. This portion must be cut off in the rolling mill and goes back to the steel furnace as scrap.

Ingotism, the formation of large crystals of steel, caused by too slow cooling or casting at too high a temperature, is a serious defect in ingots which causes the steel to be weak and low in ductility. The bad effects of ingotism may be largely or entirely corrected by careful rolling or forging. The compression of the metal crushes and reduces the size of the crystals, imparting to the steel a much superior degree of strength and ductility. Care must be taken in the initial rolling or forging to avoid the formation of cracks which cannot subsequently be welded up.

Segregation of the impurities in steel ingots is caused by the fact that most impurities, notably carbon, phosphorus, and sulphur, are less soluble in iron when solidified than while molten. In consequence, a part of the impurities in the iron are progressively rejected by each layer of metal as it solidifies, being absorbed by the still molten portion, the net result being a tendency toward concentration of the impurities in that part or parts of the ingot which solidify last. Segregation cannot be altogether prevented, but it may be lessened by the addition of elements such as aluminum or titanium, which have the effect of quieting the steel. Casting in narrow ingots is also effective, but is not practicable in all cases because it would take so long to cast many small ingots from one large ladle that the first metal would be too hot if the last metal were not too cold.

THE HEAT TREATMENT OF STEEL

Practice of Hardening, Tempering, Annealing, and Case Hardening *

474. General. If steel containing 0.6 per cent or more carbon be heated to a bright red heat and then rapidly cooled, as by plunging into water, it becomes very much harder, but at the same time much more brittle. If the hardened steel be heated to a temperature between 200° and 300° C. it will become softened or " tempered " and the brittleness largely removed, the degree of softness being directly dependent upon the temperature of tempering. If the steel is heated to the hardening temperature and then cooled very slowly it will be "annealed," i.e., rendered as soft as that particular steel can be made to be.

475. Hardening Steels. Every carbon steel possesses a certain critical range of temperatures within which important molecular changes occur in cooling. In general this range is from a low yellow down to a dull red heat. (From about 900° to about 690° C. for steels containing sufficient carbon to harden usefully.)

These molecular changes do not take place instantly, and they will therefore be retarded by shortening the time of passing through the critical range of temperatures. The amount of retardation is directly dependent upon the rapidity of cooling. If the cooling could be made instantaneous a maximum degree of hardness would be obtained, and lesser degrees of hardness are obtained by various rates of cooling after having heated the steel to just the proper temperature. For instance, some degree of hardening is obtained by quenching in molten lead; a greater degree by quenching in heavy oil; water makes it harder still; and so on, extreme hardness being obtained by quenching in ice-water, ice-brine, mercury near its freezing-point, etc. In all cases the degree of hardening obtained by any treatment will be dependent upon the amount of carbon present, and other elements, such as manganese, chromium, tungsten, etc., have not only a marked effect upon the hardness obtained, but they may greatly change the location of the critical range of temperatures, in some cases reducing it below atmospheric temperatures so that hardening may be accomplished by air-quenching.

476. Tempering Steels. Hardened steel is too brittle and too fragile for most uses without some degree of "tempering." The fact that

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* The effect of various heat-treatments upon the constitution and properties of steels will be discussed at a later point.

tempering may be accomplished at temperatures far below the critical range is due to the circumstance that hardened steel is in a state that is not natural to it at atmospheric temperatures, i.e., it is not in equilibrium. It does not change its state simply because of the rigidity and immobility of the material, which does not allow sufficient molecular freedom for the alteration to take place. Only a relatively low degree of heating is sufficient to materially decrease this rigidity and increase molecular activity, resulting in a degree of loss of brittleness and hardness in proportion to the temperature attained, and, to a lesser extent, in proportion to the time allowed at that temperature. Very often the steel is again quenched after the desired tempering heat is reached in order to prevent overheating by heat conducted to the hardened portion from the balance of the piece.

The degree of heating in tempering carbon steels is plainly indicated by a film of oxide which forms on polished surfaces and shows a succession of colors dependent upon the temperature and consequent thickness of the oxide film. These colors merge into one another gradually, but those usually distinguished, with the temperatures and the class of tools for which they indicate a proper degree of hardness, are as follows:

Color.	Approx. Temperature.	Tools so Tempered.
Pale yellow.........	220° C.	Engraving tools, fine drills, etc.
Straw.............	230° C.	Steel-cutting drills, milling cutters, etc.
Light brown........	243° C.	Dies, taps, rock-drills, etc.
Brown.............	255° C.	Wood-cutting tools, etc.
Brown-purple.......	265° C.	" " " "
Purple.............	277° C.	Cold chisels for steel and iron, etc.
Bright blue.........	288° C.	Axes, hacksaws, etc.
Pale blue..........	297° C.	Screwdrivers, needles, etc.
Dark blue..........	316° C.	Wood-saws, springs, etc.

477. Annealing Steels. Annealing has for its purpose (1) the relieving of any internal strains originating during cooling or caused by working, (2) the restoration of the grain of the steel to the minute size which is so desirable, and (3) the softening of the steel after hardening. The usual annealing temperatures are between 200° and 500° C. The heating must be done very carefully and uniformly out of contact with the fuel, and the pieces must be supported so that they will not become distorted while hot. For any refinement of the grain the heating must be carried above the critical temperature above discussed. Usually the steel is brought to a point just above the critical temperature and then cooled very slowly either by leaving it to cool down with the furnace or by removing it and letting it cool under a muffle. Small objects are enclosed in iron boxes or pots, and packed in charcoal or similar material to prevent decarburization. In principle, annealing means simply carrying the tempering process to the extreme by heating it to a high degree and cooling as slowly as possible.

478. Case-hardening Steels. Case-hardening is a form of cementation applied to low- or medium-carbon steels in order to impregnate them with carbon to a depth of perhaps one-fourth of an inch of less, thus securing a high-carbon case which may subsequently be hardened by quenching. The advantage gained by this treatment is that a surface is produced which will withstand wear, abrasion, cutting, or indentation and at the same time the core is left soft and tough so that the shock resistance of the material is not impaired. Case-hardening is especially applicable to the construction of armor-plate, safes and vaults, the moving parts of machinery which are subjected to both shock and wear, such as crank shafts, pivots and axles, gears, etc., also for the bearings and knife-edges of weighing machinery, and for many other purposes in machine and implement construction. For many of the purposes above listed certain of the alloy steels which combine great hardness with great toughness are now often preferred.

The steel used for case-hardening usually is one containing from 0.1 to 0.2 per cent carbon originally, and the operation is usually applied to the finished casting, forging, or otherwise fabricated object, so that no machine work need be done on the hardened surface.

The general method of case-hardening consists in heating the steel in contact with carbonaceous matter such as potassium ferro-cyanide, charcoal, barium carbonate, bone dust, charred leather, etc. The usual temperature of carbonation is about 900° C. A more rapid penetration of the carbon may be secured by the use of higher temperatures, but this practice is attended by the danger of the growth of coarse crystals in the interior at the temperature of carbonation, resulting in loss of toughness and strength unless the steel is subsequently reheated to restore the grain size. A time of from two to twelve or more hours is required for the process, depending upon the temperature of the furnace and the class of carburizer used. Many special or alloy steels are often treated by a case-hardening process with very beneficial results. Nickel and chrome steels are especially valuable steels for case-hardening.

Occasionally it is the practice to secure the hardening of steel which has thus been surface carburized by quenching the steel as it comes from the furnace. A far better practice, however, is to allow it to cool, and then reheat and harden in the usual manner. This operation not only tends to remove any lack of toughness caused by coarse crystalline growth, but also causes a diffusion of the carbon inward, leaving a less distinct plane of weakness between the carburized shell and the unaltered core.

THE PROPERTIES AND USES OF STEELS

STRUCTURE AND CONSTITUTION

479. The Constituents of Steels. The normal constituents of steels and irons have already been declared to be *ferrite*, which is theoretically pure iron entirely free from carbon, *cementite*, which is the carbide of iron, Fe_3C, and *graphite*, which is practically pure amorphous carbon. We must now recognize the existence of various modifications and solutions of these constituents whose existence is dependent upon the amount of carbon present and the rate of cooling from solution. These modifications of the normal constituents can only be considered in connection with the consideration of the behavior of iron carbon solutions in cooling.

480. Compounds and Solid Solutions. Eutectics. Steels in general, like wrought iron and cast irons, are not purely chemical compounds of iron with carbon, etc., but are in the nature of metallic alloys consisting of an intimate mixture or solution of metals with non-metals, forming when melted a homogeneous fluid. This molten steel is composed of liquid carbide of iron dissolved in liquid iron * and as the solution cools and freezes the carbide and iron remain a solution forming when solidified a " solid solution."

A solid solution differs from a mixture in that there is no separation of the constituents in freezing, and even the microscope is unable to distinguish the different components. The solution appears to be a simple homogeneous body like a chemical compound. On the other hand, a solid solution differs from a chemical compound principally because it may contain widely varying amounts of each component while a compound must always hold certain definite relative amounts of each component, and in some multiple of their atomic weights.

There is a limit, however, to the amount of carbon which can be carried with iron out of the liquid state in solid solution. This limit is reached when the iron contains about 1.7 per cent of carbon (Sauveur). No solid solution of carbon and iron will form containing more than about 1.7 per cent of carbon, and any additional carbon must remain out of solution either as cementite or as graphite and ferrite. All irons, therefore, which contain more than the amount of carbon which can be held in solution (more than 1.7 per cent C.) are rightly classed as cast

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* According to the views of a number of authorities steels are solutions of carbon in iron rather than solutions of carbide of iron in iron.

irons, or products intermediate between cast iron and steel, and not as steels.

Eutectics. When a solution of two dissimilar constituents is cooled, the freezing-point of one or the other of the constituents will normally be reached before the freezing-point of the solution as a whole is reached. There will always be, however, a certain definite solution of the constituents whose freezing-point is reached before either of the individual constituents has begun to crystallize out. This particular solution is called the " eutectic solution " and the substance formed when the eutectic solution crystallizes out is called the " eutectic " or, in the case of solid solutions, " eutectoid."

PHENOMENA OF SLOW COOLING OF IRON-CARBON ALLOYS

481. Freezing of Iron-carbon Alloys. If a molten alloy or solution of carbide of iron (cementite) in iron contains an excess of the carbide over the eutectic ratio, carbide of iron will crystallize out in cooling until the remaining solution is of eutectic composition, when it will all crystallize out together. Such an alloy is called a " hyper-eutectic " alloy. On the other hand, if an excess of iron is present " austenite," the solid solution of iron and carbide of iron which is normal at all temperatures above about 880° C., will crystallize out and continue to do so until the remaining solution is of eutectic composition. Such an alloy is called a " hypo-eutectic " alloy. The eutectic formed is a saturated solution of " austenite " * and cementite whose composition is definitely fixed at 95.7 per cent iron and 4.3 per cent carbon.

The freezing of iron-carbon alloys is depicted graphically by the diagram of Fig. 241. The significance of the diagram may be explained as follows:

With any hypo-eutectic alloy the temperature at which the austenite will begin to freeze is indicated by the line *AB*, and the temperature at which the freezing of austenite is completed is indicated by the line *AD*. Thus if an alloy contains 1 per cent carbon, its austenite will begin to freeze at about 1430° C. and it will have become wholly solid at about 1200° C. Any alloy of carbon and iron will behave similarly (passing through a transition stage and finally becoming a solid solution of cementite and γ-iron) so long as the carbon content does not exceed 1.7 per cent. When the carbon content lies between 1.7 per cent and 4.3 per cent a selective precipitation of austenite occurs until the liquid solution becomes so impoverished in iron that its composition approaches the eutectic ratio, and final solidification takes place when the eutectic

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* Austenite is defined in Art. 483.

is reached. Thus an alloy containing 3 per cent carbon will begin to precipitate austenite at a temperature of about 1250° C. and all of the austenite will have crystallized out before a temperature of about 1135° (line *DBE*, Fig. 241) is reached. As the remaining solution becomes impoverished in iron and continues to cool, its position moves along the line *AB* of the diagram until the eutectic composition is reached at *B*, when further cooling causes it to crystallize out of solution.

With any hyper-eutectic alloy (more than 4.3 per cent carbon) cooling causes cementite to begin to crystallize out as soon as the line *CB*, Fig. 241, is reached. The liquid solution thus becomes progressively improverished in cementite, and with continued cooling its position moves along the line *CB* until the eutectic is formed upon cooling below point *B*.

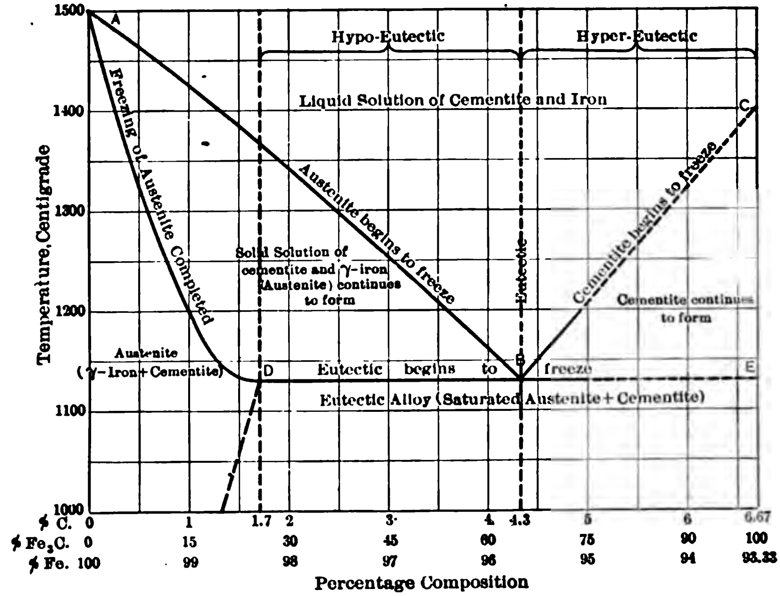

FIG. 241.—The Freezing of Iron-carbon Alloys.

(A number of authorities consider that the saturation point of carbon in iron is 2.2 per cent carbon instead of 1.7 per cent carbon. According to this view the point *D* in Fig. 241 should represent 2.2 per cent carbon, and the line of demarcation between cast iron and steel is at 2.2 per cent carbon.)

482. Changes in Cooling below the Freezing-point. When the solid solutions of carbon and iron are further cooled they are found not to be stable, but decompose at various temperatures, dependent upon the carbon content. Austenite decomposes into cementite and ferrite, and as the cooling continues the ferrite successively assumes two allotropic forms at temperatures below that temperature at which the γ form of ferrite exists. These allotropic forms of ferrite are β-iron and α-iron.

The molecular change in iron passing from the γ form to the β form, and subsequently from the β form to the α form, is attended by the evolution of a certain amount of heat which causes a " retardation " in the rate of cooling. Furthermore, a third retardation occurs in iron-carbon alloys when the temperature is reached at which the residual solution of the original solid solution (after precipitation of ferrite or cementite) finally decomposes into its constituents, ferrite and cementite.

These three temperatures at which retardations occur in cooling are called the " critical points " in cooling. They are usually designated as A_1, A_2, and A_3, respectively, in order of increasing temperature. The range of temperature included between points A_1 and A_3 is known as the " critical range " of temperatures.

Exactly the reverse phenomena occurs in heating steel through this same range, a sudden absorption of heat and a consequent falling off in the rate of heating being observed at each critical point. The critical points on heating are slightly higher than the corresponding critical points in cooling, owing to a lag or hysteresis effect, the physical change not occurring immediately when the temperature which should produce it is reached. The critical points in heating are usually distinguished from the corresponding points in cooling by designating the former Ac_1, Ac_2, Ac_3 and the latter Ar_1, Ar_2, Ar_3.* As the amount of carbon in the steel increases, the Ar_3 and Ar_2 points approach each other until they coincide, when the carbon content is about 0.5 per cent, and the critical point is then designated $Ar_{3,2}$. Further increase in carbon to about 0.85 per cent causes the $Ar_{3,2}$ point to coincide with Ar_1 and the resultant single critical point is designated $Ar_{3,2,1}$.

The approximate position of the critical points in cooling various steels is indicated by the time-temperature curves, or cooling curves, of Fig. 242.

By observing the position of the critical points in cooling for a considerable number of steels whose carbon content varies over a wide range, the complete decomposition diagram of iron-carbon solid solutions shown in Fig. 243 may be derived. The significance of this diagram may be explained as follows:

Consider first a hypo-eutectoid alloy containing 0.2 per cent car-

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* *r* stands for the French *refroidissement*, meaning cooling, and *c* for the French *chauffage*, heating.

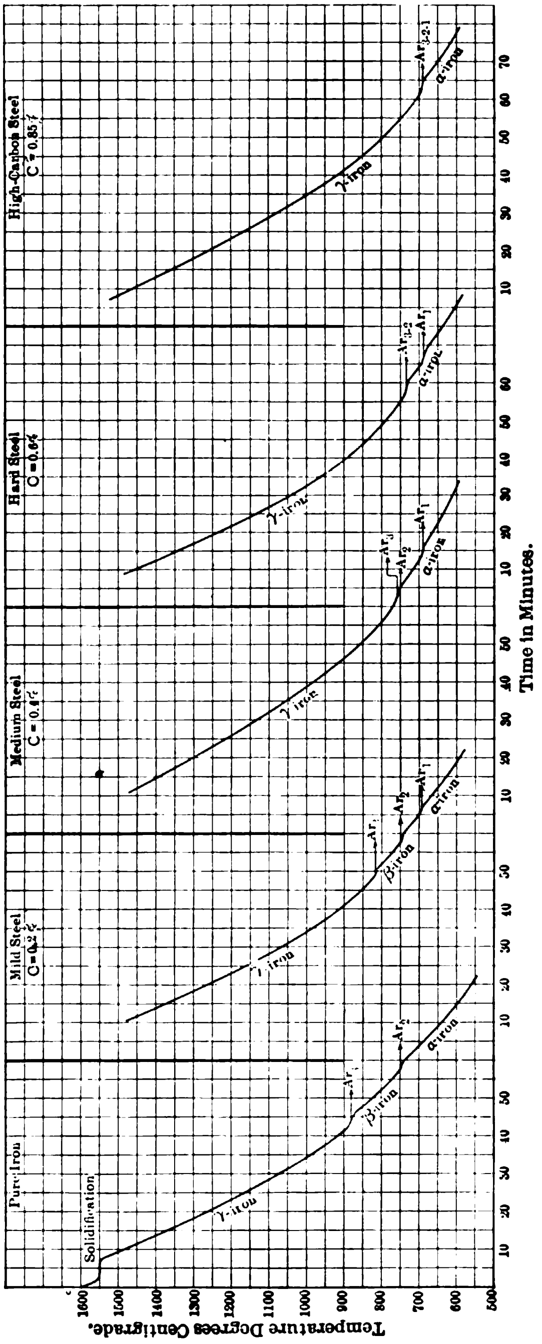

FIG. 242.—Critical Temperatures, Cooling Curves for Various Steels.

bon. In cooling from above 900° C. the first critical point, Ar_3, is encountered at a temperature of about 845°. (Intersection with line *FG*, Fig. 243.) Ferrite now begins to be precipitated from the austenite, being transformed from the γ form to the β form. β iron continues to form until the second critical temperature, Ar_2, is reached at about 760°, when the β iron begins to assume the α modification. As the remaining solid solution becomes more and more impoverished in iron through precipitation of ferrite its position moves along the line *FGM* until, when the critical point Ar_1 is reached, at a temperature of about 690°, the austenite is of eutectoid composition (0.85 per cent carbon) and on further cooling becomes pearlite.

If the hypo-eutectoid alloy were one containing 0.6 per cent carbon, its ferrite would begin to be precipitated as iron when the critical point $Ar_{3,2}$ is reached, at a temperature of about 745°. (Intersection with line *GM*, Fig. 243.) The selective precipitation of ferrite in the α form will continue with further cooling until the remaining solid solution is again of eutectoid composition, when it will be converted into pearlite at the critical point Ar_1.

Now consider a hyper-eutectoid alloy containing 1.2 per cent carbon. In cooling from 1000° C., for instance, the first transformation will occur when the line *DM*, Fig. 243, is encountered at a temperature of about 900°. Cementite now begins to be precipitated from the solid solution and continues to crystallize out until the remaining austenite has reached the eutectoid composition, when it again becomes transformed into pearlite.

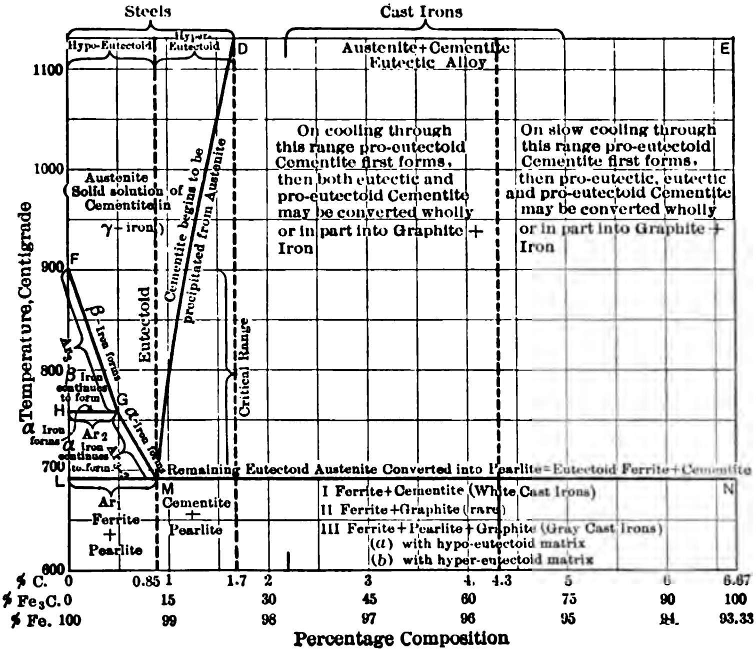

FIG. 243.—Solid Solution Decomposition Diagram.

Lastly, considering the changes which occur upon cooling the eutectic alloy of cementite and austenite below its freezing-point (about 1135° C.), we find that pro-eutectoid cementite (cementite whose formation immediately precedes the formation of the eutectoid) first forms, followed by the decomposition of a part or all of the cementite into ferrite and graphite. This latter conversion process is greatly affected by the presence of the various impurities such as silicon, manganese, phosphorus, and sulphur, which are always present in cast irons, and the precipitation of graphite in particular is especially affected by the rate of cooling.

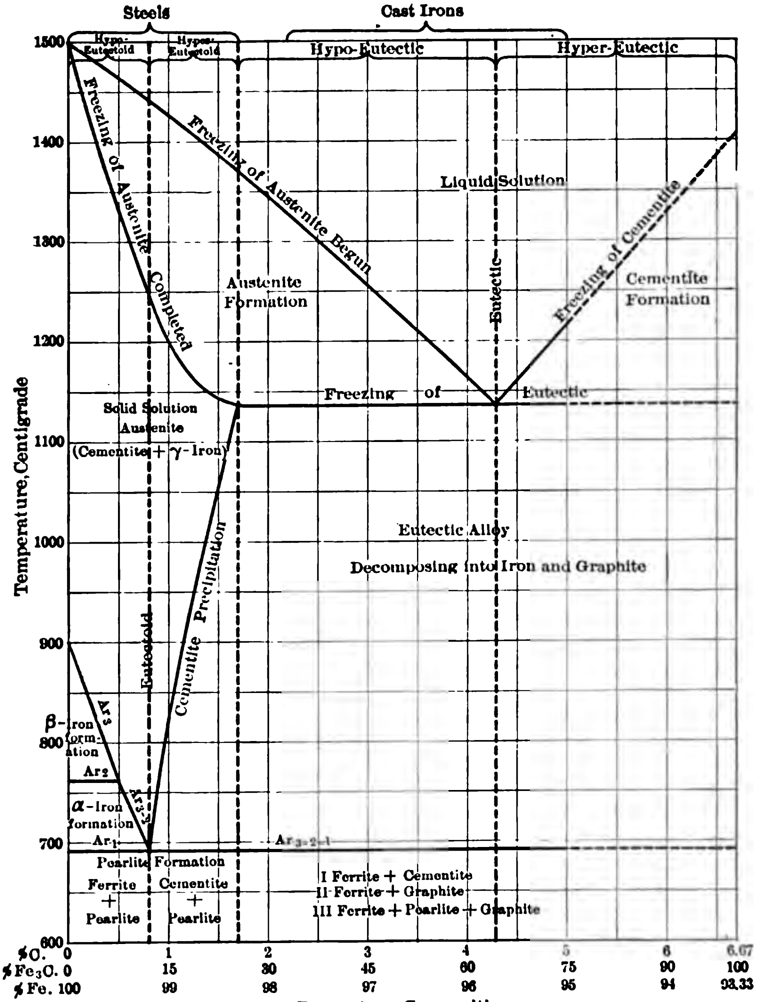

Fig. 244.—Equilibrium Diagram for Iron-carbon Alloys.

According to the relative potency of these various factors the ultimate constitution of the iron may be that of white cast iron or gray cast iron, or even a combination of the two. (Reference is here made to the discussion of the constitution of cast irons in Arts. 353 to 361 inclusive, Chap. XII.)

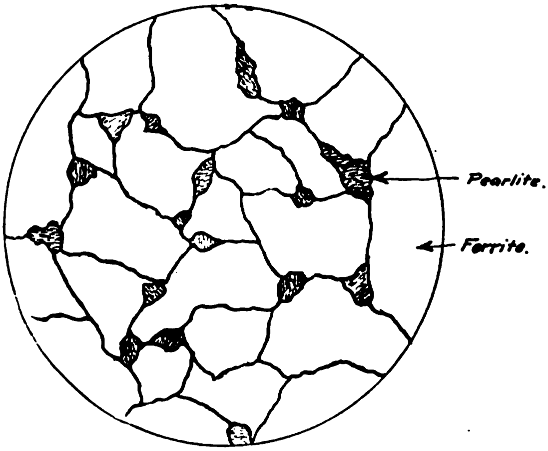

FIG. 245.—Micro-structure of Low-carbon Steel. Carbon = 0.08%. (Arnold.)

The complete equilibrium diagram for iron-carbon alloys, Fig. 244, is simply a combination of Figs. 241 and 243. The complete history of the cooling of any iron or steel may be followed through the equilibrium diagram of Fig. 244, just as has been done separately for the ranges of temperatures above and below the freezing-point.

The structure of slowly cooled steel as revealed under the microscope will, in the case of a low-carbon steel, be a mass of ferrite with isolated particles of pearlite occurring at the junction of the grains of ferrite (Fig. 245). For a medium-carbon steel the proportion of pearlite is increased and the ferrite correspondingly decreased (Fig. 246). The structure of eutectoid steel is that of a mass of pearlite grains which individually appear as shown in Fig. 179. Lastly, in hyper-eutectoid steel the excess cementite over the amount required to form pearlite will be rejected to the boundaries of the pearlite grains, the appearance of the structure being as shown in Fig. 247.

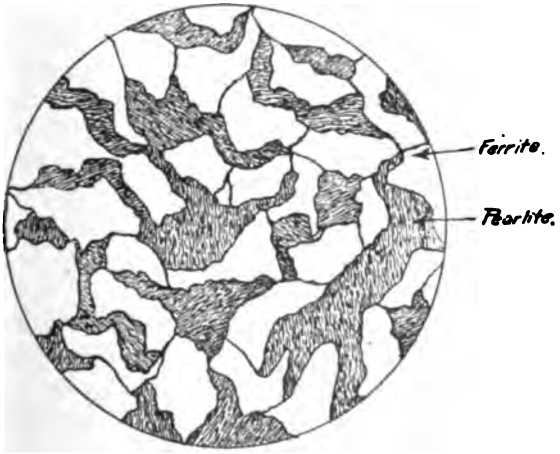

FIG. 246.—Micro-structure of Medium Steel. Carbon = 0.38%. (Arnold.)

PHENOMENA OF RAPID COOLING FOLLOWED BY VARIOUS REHEATING TREATMENTS

483. Effect of Various Heat Treatments upon the Structure and Constitution of Steels. The practice of applying various heat treatments to steels has been discussed above in Arts. 474 to 478 inclusive. The actual changes produced in constitution and structure could not be considered at that point, however, because the constitution and slow-cooling phenomena of steels had not then been considered.

Hardening. When carbon steels are heated above the transformation range (above the line *FGMD*, Fig. 243) the aggregate of ferrite and cementite normal to slowly cooled steels is converted into austenite, and upon subsequent rapid cooling the normal transformation of austenite back to ferrite and cementite is prevented, at least in part, because of lack of time afforded at the transformation temperatures. In the ordinary practice of hardening steels the partial transformation of austenite back to ferrite and cementite gives rise to certain transitory forms which are known as "martensite," "troostite," "sorbite" and "pearlite." These various constituents of hardened steels are defined as follows by the Committee on Nomenclature of the Microscopical Substances and Structures of Steel and Cast Iron of the International Association for Testing Materials: *

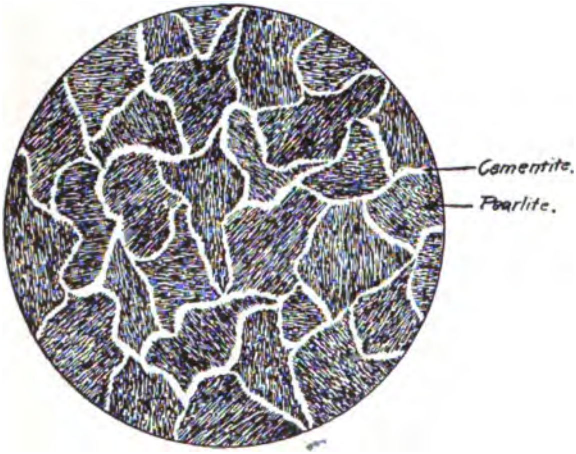

FIG. 247.—Micro-structure of High-carbon Steel. Carbon = 1.4%.

Austenite. "The iron-carbon solid solution as it exists above the transformation range or as preserved with but moderate transformation at lower temperatures, e.g., by rapid cooling, or by the presence of retarding elements (Mn, Ni, etc.), as in 12 per cent manganese steel and 25 per cent nickel steel."

Martensite. "The early stage in the transformation of austenite,

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* Proc. Sixth Congress, New York, 1912.

characterized by needle structure and great hardness, as in hardened high-carbon steel." (Its nature is much disputed.)

Troostite. " Probably aggregate. In the transformation of austenite, the stage following martensite and preceding sorbite (and osmondite if this stage is recognized.) "

Sorbite. " In the transformation of austenite the stage following troostite (and osmondite if this stage is recognized), and preceding pearlite."

Pearlite. " The iron-carbon eutectoid, consisting of alternate masses of ferrite and cementite."

Austenite has already been declared to be a solid solution of carbon, or more probably, Fe_3C and γ iron. It is stable above the line *LMN*, Fig. 243, and may have any carbon content up to the saturation point indicated by line *MD*. Austenite is very hard, but not as hard as martensite. In hardened high-carbon steel it forms a ground mass which is interspersed with martensite.

Martensite is usually considered to be a solid solution of carbide of iron, Fe_3C, in iron, the latter being partly in the α form and partly in the β form. It is not in equilibrium in any part of the diagram, but represents a metastable condition in which the metal is caught during rapid cooling. It is very hard and is the chief constituent of hardened high-carbon steels and of medium nickel and manganese steels. In less fully transformed steels it is associated with austenite, and in more fully transformed steels with troosite and even with ferrite or cementite.

Troostite is an uncoagulated conglomerate of the transition stages. The degree of completeness of the transformation represented by it probably varies widely, as does its carbon content. It arises on cooling through the transformation range at an intermediate rate, or on reheating hardened high-carbon steel to about 400° C. It occurs associated with martensite, and is intermediate in hardness between that of the martensitic and the pearlitic state corresponding to its carbon content. Tempering remarkably increases its ductility and lowers its hardness and elastic limit.

Sorbite is believed to be " essentially an uncoagulated conglomerate of irresoluble pearlite with ferrite in hypo-eutectoid steels and with cementite in hyper-eutectoid steels, respectively, but that it contains some incompletely transformed matter." It arises in reheating hardened steels a little above 400°, but not to 700°, at which temperature it coagulates into granular pearlite. It also arises in quenching small pieces of steel in a medium which cools the metal slowly, and in water quenching from a temperature near the lower end of the transformation range. It is softer than troostite, and is habitually associated with pearlite. It is slightly less ductile than pearlitic steel of the same carbon content, but greatly excels the latter in strength and elastic limit. In fact a sorbitic steel possessing the same degree of ductility as a higher carbon pearlitic steel will greatly excel the latter in strength and elastic limit.

Pearlite is a definite conglomerate of ferrite and cementite containing about six parts of the former to one of the latter. When pure, its carbon content is about 0.85 per cent (often stated to be 0.9 per cent). It results from the completion of the transformation of eutectoid austenite accomplished by the slow cooling of any iron-carbon alloy below the transformation range, or held at temperatures within or slightly below that range long enough to allow the ferrite and cementite to coagulate. It is called " granular " pearlite when the cementite forms fine globules in a matrix of ferrite, and " laminated " or " lamellar " pearlite when the ferrite and cementite exist as alternate parallel lamellae. Its ferrite is stable, but its cementite is metastable, tending to transform into ferrite and graphite.

The cooling conditions which are favorable to the formation of the various constituents of hardened carbon steels are illustrated graphically by the diagram of Fig. 248.* An effort has been made to make the diagram self-explanatory, but it may be well to emphasize the facts which it depicts.

(1) If an eutectoid steel is either (*a*) rapidly cooled to atmospheric temperature after slow cooling to the temperature *A* at which austenite is undergoing transformation to martensite, or (*b*) cooled from above Ar_1 to atmospheric temperature very rapidly, as by quenching in iced brine or ice water, the constitution of the hardened steel will be austenite primarily, but a certain amount of martensite will be present even though the steel be quenched from above Ar_1.

If the steel had been a hypo-eutectoid steel or a hyper-eutectoid steel, the constitution would be the same except that in the first case free ferrite precipitated above Ar_1 would be also present, and in the second case free cementite would be present.

(2) With treatment (*a*) carried out with respect to temperature *B*, corresponding to the temperature of formation of martensite, or treatment (*b*), the cooling being slightly less rapid than before, the constitution will be primarily that of martensite, but some austenite or some troostite, or both, will be present. Free ferrite will also be present in a hardened hypo-eutectoid steel and free cementite in a hardened hyper-eutectoid steel just as before.

(3) With treatment (*a*) carried out with respect to temperature *C*, corresponding to the temperature of formation of troostite, or treatment (*b*) with still less rapid cooling, the constitution may be primarily

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* This diagram is to a slight degree based upon a diagram used for a similar purpose by Sauveur, " The Metallography of Iron and Steel," Lesson XII, p. 16.

troostite, but the troostite will always be associated with a greater or lesser amount of martensite, though not with sorbite. Free ferrite or free cementite will be present under the conditions above noted.

(4) With treatment (*a*) carried out with respect to temperature *D*, corresponding to the temperature of formation of sorbite, or treatment (*b*) with very slow cooling, the constitution will be sorbite associated with more or less pearlite, together with free ferrite or cementite as before.

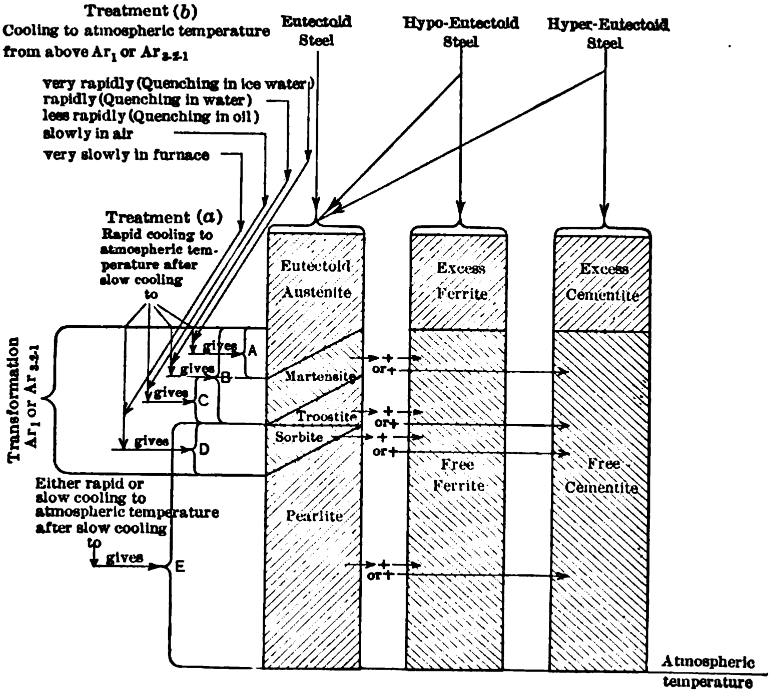

FIG. 248.—Diagram Showing Transformations in Hardening Steels.

(5) When slow cooling is carried to the temperature range *E*, corresponding to the formation of pearlite, the constitution will be entirely pearlite together with free ferrite, or cementite, except in the uppermost part of this range, where it overlaps *D*, making the occurrence of some sorbite possible.

The temperatures *A*, *B*, *C*, *D*, and *E* cannot be definitely stated, and the diagram is intended to show that they are somewhat indefinite. The whole temperature range from *A* to *D* is simply the transformation point Ar_1 or $Ar_{3,2,1}$ on the equilibrium diagram.

The diagram is also intended to show that the constitution of hardened steels does not abruptly change from that normal to one constituent to that normal to another constituent, but changes gradually, owing to the intermingling of these constituents. The individual constituents may in some cases be sharply differentiated from one another, as is the case with austenite, martensite, and troostite. Troostite, sorbite, and pearlite are not so sharply differentiated from one another, and intermediate transformation stages are frequently observed.

Finally, the fact must not be lost sight of that the hardness obtained by any treatment of steel is not alone dependent upon the heat treatment and consequent prevailing character of the constituents, e.g., martensitic, sorbitic, etc., but that the character of each of these constituents is dependent upon its carbon content, and therefore the hardness obtainable by a given hardening treatment is directly proportional to the amount of carbon in the steel used.

An explanation of why steels are hardened by the treatments above discussed is a very difficult thing to undertake, and authorities are by no means in agreement on any one theory of hardening. A considerable number of more or less radically different theories have been proposed and have found support by competent authorities. One theory, however, has been supported by a majority of the more eminent specialists—the so-called " beta-iron " or " allotropic " theory—and this theory alone will be herein discussed.

The beta-iron or allotropic theory proposed by Osmund contends that iron is present in hardened steel chiefly in the β form, and that carbon, or more probably cementite, is in solution chiefly in β-iron, to which fact hardness is attributed, β-iron being very hard. That α-iron is also present in a measure is undeniable, however, since hardened steels possess magnetism and α-iron is the only one of the allotropic forms which is magnetic.

It is of course a matter of universal observation that the presence of carbon is essential to hardening, and that the degree of hardness attainable is proportional to the amount of carbon present. According to the beta theory of hardening, however, the carbon does not directly induce hardness, but does so indirectly through its ability to hold the iron in the β form and prevent the transformation to the α form. The fact that the degree of hardness attainable is proportional to the amount of carbon present is explained by the fact that the greater the proportion of carbon present, the stronger will be the influence tending to preserve the iron in the β form, the proportion of the latter, and not the amount of carbon present, being the real factor upon which the degree of hardness attainable depends. The internal pressure caused on the transformation of γ-iron to β-iron (due to the expansion which accompanies this action) is considered to be a minor factor contributing to the final hardness. (A number of eminent authorities deny the possibility of the existence of the beta form of iron, and they reject the beta-iron theory of hardening *in toto.*)

Tempering. The necessity for tempering hardened steels, and the explanation of the fact that hardened steels can be tempered by reheating to only moderate degrees far below the critical range of temperatures, has been explained above. There remain to be explained, however, the changes in constitution and structure which take place when hardened steels are tempered.

It will first be necessary to recall that hardened steels may theoretically be either austenitic, martensitic, troostitic, troosto-martensitic, or troosto-sorbitic. Sorbitic and pearlite steels are not really hardened and therefore cannot be tempered. The tempering of each of the other classes of steel will be separately considered.

The diagram of Fig. 249 illustrates graphically the transformation which, theoretically at least, should take place when hardened carbon steels are tempered.*

Austenitic steel is not produced by ordinary commercial methods of hardening except possibly in the case of certain alloy steels like manganese steel. Under most carefully controlled conditions, a carbon steel which is partially austenitic may, however, be derived. The transformation which theoretically will occur in the austenitic portion of such a steel is shown by Fig. 249 (*a*). The austenitic is shown to be undergoing transformation to martensite as soon as heating is begun, and martensite alone exists when a temperature of 200° C. is reached. The martensite begins to be transformed to troostite at 200°, the latter alone remaining when a temperature of 400° is reached. Further heating above 400° causes the gradual conversion of troostite into sorbite, and the latter alone exists above 600° C. If the heating were continued past the critical temperature austenite alone could exist. (Only the constituents of hardened steels which resulted from transformations of eutectoid austenite are now being considered. Free ferrite or free cementite, which are always present in hardened hypo-eutectoid or hyper-eutectoid steels, remain unaltered by tempering operations and can, in fact, be affected only by heating within the critical range, causing them to go back into solution with austenite again.)

Most observers have noted, however, that austenitic steel, on being heated, begins to be transformed from the austenitic to the troostitic

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* This diagram, except for minor additions, and the accompanying discussion is taken from Sauveur's "The Metallography of Iron and Steel."

condition directly, the intermediate martensitic form not being observed. This behavior is illustrated by Fig. 249 (*a′*). Notwithstanding the fact that the martensitic form is not observed, it is not impossible that it may have been formed and still have escaped detection simply because the succeeding transformation of martensite to troostite follows very quickly.

Martensite is a common constituent of commercially hardened steels, being far less unstable than austenite. The tempering of a martensitic steel is illustrated by Fig. 249 (*b*). Conversion of martensite into troostite begins almost immediately when heating is begun and no martensite exists if heating is carried beyond 400° C. Further heating causes conversion of troostite into sorbite, and sorbite alone exists between 600° and the critical temperature.

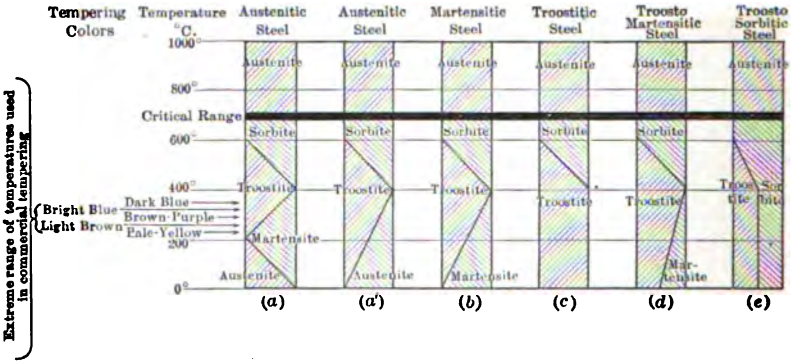

FIG. 249.—Diagram Depicting the Tempering of Hardened Steel. (Sauveur.)

Troostite is a still more common constituent of commercially hardened steels because it is decidedly more stable than austenite or even martensite. When troostitic steel is tempered, Fig. 249 (*c*), no change is effected unless heating be carried beyond 400°, when the changes above noted for other steels again take place. If wholly troostitic steels were encountered in practice no tempering would be required, but since some martensite is usually present in even the most distinctly troostitic steel, tempering is required. The change which takes place is the gradual transformation of the martensite to troostite as shown in Fig. 249 (*d*), no martensite being present above 400° C.

Troosto-sorbitic steels are a rare possibility among commercially hardened steels. The degree of hardening is so slight and the constituents so stable that tempering does not produce any effect unless carried above 400° C., when the troostite is gradually converted into sorbite.

The extreme range of temperature used in commercial tempering is, as indicated on the left of the diagram, only from about 200° to slightly above 300° C. It is evident, therefore, that the only constituents encountered in tempered eutectoid steels are troostite and martensite. In this statement austenitic steels are not taken into account because they are not encountered in practice, and troostitic and troosto-sorbitic steels might also be left out of consideration because they require no tempering and are not affected by heating to the ordinary temperatures. The portion of the diagram which represents the possible constitution of steels which have been tempered after hardening is that portion of Figs. *b* and *d* comprised between temperatures of about 200° and about 300° C.

Two considerations which affect the practice of tempering steels cannot be shown by the diagram. First, the transformation of one constituent to the succeeding form is not solely dependent upon the temperature attained, but is also dependent upon the relative rapidity or slowness with which the temperature is reached, and upon the time allowed at this temperature. Slow heating, or holding at a given temperature for a measurable interval, will produce a greater degree of tempering than would otherwise be effected at a given temperature. Second, when, as is often the case in practice, the reheating of the hardened steel is done in such a manner that, if not arrested quickly, the temperature would continue to rise after reaching the desired tempering heat, it is necessary to cool the metal quickly by immersion in some quenching medium. This explains the reason for the common tempering practice of quenching from a rising temperature. If the temperature is not rising after the desired tempering effect is reached it is immaterial whether quenching follows or not. As a matter of convenience quenching almost invariably follows reheating in the commercial heat treatment of steels.

Annealing. The statement is made above that annealing is done with any or all of the following purposes in view: (1) The relieving of any internal strains originating during cooling or caused by working, (2) the restoration of the grain of the steel to a minute size, and (3) the softening of steel after hardening. The accomplishment of each of these objects will be separately considered.

Cooling strains originate owing to the circumstance that all portions of a piece of steel cannot be cooled evenly. All carbon steels contract rapidly while cooling and, since cooling proceeds from the exterior inward, the contraction of the exterior of a piece of steel tends to compress the interior and cause it to flow. The action is aggravated by the fact that after the exterior has passed that critical range in cooling, the interior stops contraction or expands while passing the critical points.

The effect is most marked when the section is large, or where an abrupt change from a large to a small section occurs. Under ordinary circumstances cooling strains are not excessive except when steel has been rapidly quenched from a high temperature.

Internal strains are introduced by cold working owing to the actual distortion of the crystalline elements (pearlite, ferrite, and cementite) in the direction of application of pressure, and may result in marked decrease in ductility and even induce great brittleness. An extreme example of this effect is exhibited by cold, drawn wire, which at various stages in the drawing operation must be annealed in order to make further drawing possible.

The effect of annealing in relieving internal strains is due to the increase in molecular mobility afforded by the higher temperature. The annealing temperature recommended for this purpose by the American Society for Testing Materials * is about 775° C., followed by slow cooling, the rate of cooling being dependent upon the thickness of the piece. Thick pieces may require very long exposure to the annealing temperature followed by very slow cooling.

The coarse crystallization which results from the overheating of steel (above about 1100° C., for medium-carbon steel), not followed by hot working, constitutes a great impairment of the physical qualities of all classes of carbon steels. Low-carbon steels are principally injured in that their ductility is impaired, while medium- and high-carbon steels lose both ductility and strength.

Coarse crystallization can only be corrected by heating to above the critical range of the particular steel in hand, followed by slow cooling. The effect is the obliteration of existing crystallization and the formation of a new finely crystalline structure. Heating must not be carried much above the critical range, however, for the new crystals formed in passing this range increase in size rapidly as the temperature increases. Hypo-eutectoid steels must be heated just above the line *FG*, Fig. 243, and hyper-eutectoid steels just above the line *D*. The American Society for Testing Materials * recommends the following range of annealing temperatures for steels of the carbon content stated:

Range of Carbon Content	Range of Annealing Temperature
Less than 0.12 per cent	875 to 925° C.
0.12 to 0.29 " "	840 to 870° C.
0.30 to 0.49 " "	815 to 840° C.
0.50 to 1.00 " "	790 to 815° C.

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* Transactions, 1911.

One of the forms of coarse crystallization which is not caused by overheating, and which is peculiar to very low-carbon steel is what is called *Stead's brittleness.* When very low-carbon steel (or even wrought iron) is exposed for very long periods (a matter of several days) to temperatures ranging from 500° C. up to but not exceeding 750° C., extremely large crystals are formed which affect ductility just as overheating does. The conditions which render Stead's brittleness possible are so seldom met with in practice that the phenomenon is not often encountered. The remedy is exactly the same as if the coarse crystallization had been due to overheating, i.e., annealing by slow cooling from above the critical range.

Annealing for the purpose of rendering a hardened steel less hard or less brittle is nothing more than tempering carried to the extreme by very slow cooling following moderate heating. The changes which take place will be understood from the above discussion of tempering.

THE PHYSICAL PROPERTIES OF STEELS

484. Grades of Steel and General Properties. The following grades or classes of steels are among those most commonly recognized, their approximate tensile properties being as indicated:

Class by Uses.	Class by Manufacture, etc.	%C	Elas. Lim. Lbs. per sq.in.	Ten. Str. Lbs. per sq.in.	% Elong. in 8″
Boiler rivet....	Dead soft O. H ..	.08 –.15	25,000	50,000	30
Structural rivet	Soft O. H.......	.15– .22	30,000	55,000	30
Boiler plate ...	Soft Bess. or O. H	.08– .10	30,000	60,000	25
Structural steel	Medium O. H ...	.18– .30	35,000	65,000	25
Machinery "	Hard O. H......	.35– .60	40,000	75,000	20
Rail "	Hard Bess. or O.H.	.35– .55	40,000	75,000	15
Spring "	High Carbon O.H.	1.00–1.50	60,000	125,000	10
Tool "	High Carbon O.H. or crucible.	0.90–1.50	80,000	150,000	5

The modulus of elasticity of all grades is about 29,000,000 or 30,000,000 pounds per square inch.

485. Tensile and Compressive Strength in General. The tensile strength of steel is quite closely allied with the compressive strength, the properties revealed under one character of stress being practically identical with those revealed under the opposite character of stress. It is not necessary, therefore, to consider tensile strength and compressive strength separately, except to a slight extent. One fact which must not be overlooked in this connection is that soft or medium steel is often subjected to compressive loading under such circumstances that the stress induced does not remain purely compressive, but becomes a combination of compressive stress with bending stresses. The behavior of the material in this event is manifestly not that which is characteristic of steel in compression. When, for instance, compressive load is applied to a steel test specimen whose length is more than three or four times its diameter, or to a steel column whose length bears a large ratio to its least radius of gyration, complete failure occurs under a load which has induced an average compressive stress only slightly in excess of the yield point. Flow of the ductile metal at the yield point has caused eccentricity of stress, and failure ensues almost immediately owing to lateral flexure and the concentration of stress in the extreme fiber on one side of the section. For all practical purposes, therefore, the column strength of steel is identical with the yield point.

The principal factors influencing the strength, ductility, and elastic properties of steels are: (1) the per cent of carbon present, (2) the heat-treatment and the character and extent of the mechanical working to which it has been subjected, and (3) the content of silicon, manganese, sulphur, phosphorus, and other alloying elements. The factors are not necessarily independent factors, but their effects are usually combined. The nature and extent of the effect of heat-treatment, working, and the presence of alloying elements are inevitably dependent upon the amount of carbon present; the effects of heat-treatments and working are dependent upon the presence of alloying elements, etc. These various factors which influence the physical characteristics of steels will be separately discussed.

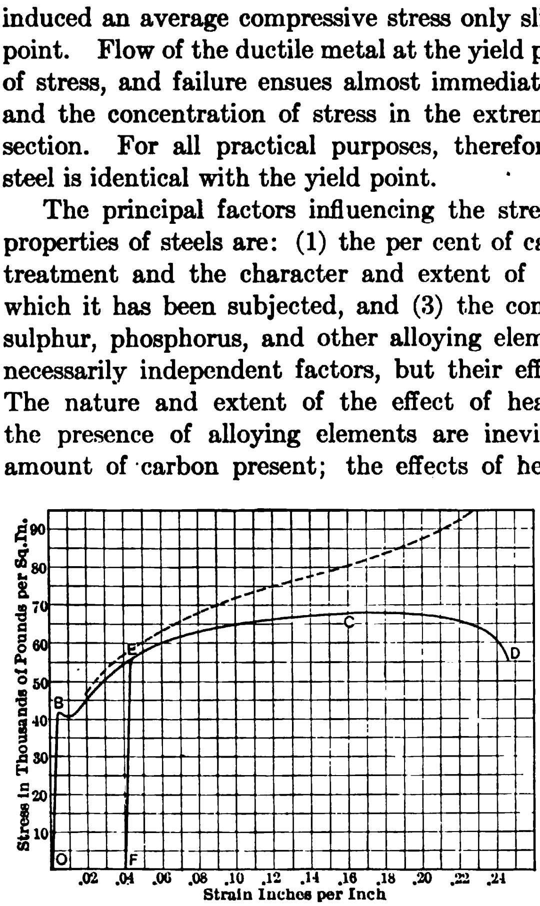

FIG. 250.—Stress-strain Curve for Mild Steel.

486. Behavior of Steel under Stress in General. The behavior of steel under stress is best studied with the aid of the *stress-strain diagram*. Fig. 250 presents a typical stress-strain diagram for a mild steel and Fig. 250*a* shows the portion of Fig. 250 between O and B to an enlarged horizontal scale. The *elastic limit* of the material (A, Fig. 250*a*) cannot usually be detected on a stress-strain diagram drawn to such a scale as to record the complete history of a test. Its position must be determined by observing the point of initial set in making a test. The *yield point B* is easily detected both in making a test (by the drop of the weighing lever of the testing machine), and from the stress-strain diagram, a more or less sharp break appearing in the curve when the yield point is reached. (With medium carbon steels an actual drop in the curve appears at the yield point owing to the fact that the metal momentarily deforms so rapidly that the stress upon a specimen is somewhat relieved.) With most steels the yield point appears at a stress not less than six-tenths of the ultimate strength. The *ultimate strength* is represented by the maximum ordinate to the stress-strain curve at *C*, and the *breaking strength D* is somewhat less than the ultimate strength for all except very non-ductile steels.

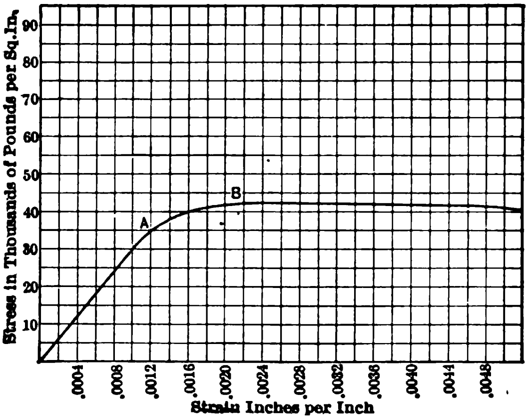

FIG. 250*a*.—Portion of Fig. 1, Enlarged Scale.

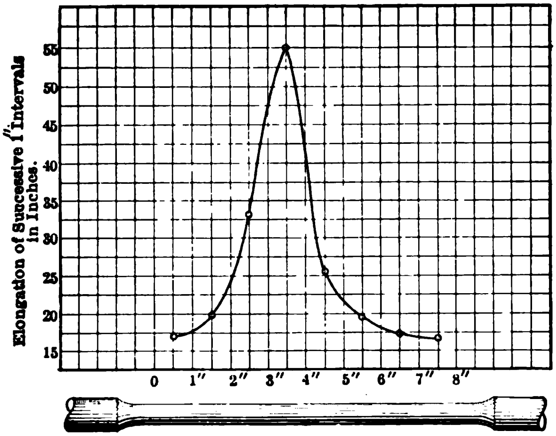

FIG. 251.—Distribution of Elongation.

The distribution of elongation of a steel specimen in tension is illustrated by Fig. 251. If uninfluenced by any local cause, a bar of homogeneous steel subjected to axial tension should fail at the center of the distance between the points of application of the load, because the flow of the metal will there be least impeded. The maximum ordinate to the curve of Fig. 251 represents the point where " necking down " occurred, since the point of maximum reduction in area must necessarily coincide with the point of maximum elongation. All steels except high-carbon steels exhibit the phenomenon of necking down, the action being most pronounced in the case of medium-carbon steels. The fact that steel test specimens are reduced in cross-section as they are elongated under stress (in obedience with the law expressed by Poisson's ratio), and finally neck down, accounts for the fact that the breaking load, according to the stress-strain diagram, is below the ultimate strength. If the stress were at all loads computed upon the basis of the actual section then existing, instead of being computed (as it always is) upon the basis of the original section, the stress-strain curve would follow such a course as is indicated by the dotted line of Fig. 250.

The modulus of elasticity can be determined from the slope of the first portion of the stress-strain diagram, but is usually computed from the observed values of stress and strain. The modulus of elasticity is strangely unaffected by the factors which influence other properties of steels and will, as above stated, be found in the neighborhood of 29,000,000 to 30,000,000 pounds per square inch for practically any class of carbon steel.

The tensile properties of various steels called for in the standard specifications of the American Society for Testing Materials are summarized in the following table:

TENSILE PROPERTIES OF VARIOUS STEELS

Character and Use of Steel.		Tensile Strength Lbs. per Sq.in.	Yield Point. Lbs. per Sq.in.	Elongation. Min. in 8 ins. Per Cent.	Elongation. Min. in 2 ins. Per Cent.	Reduction of Area. Min. Per Cent.
Rail Splice Bar Steel	Low carbon	55-65000	....	22		
	Medium carbon	68000	....	......	$\frac{1600000}{\text{u.t.s.*}}$	
	High carbon	85000	....	......	14	
	Extra high carbon	100000	....	......	10	
Structural steel for bridges	Structural	55-65000	0.5 (u.t.s.)	$\frac{1500000}{\text{u.t.s.}}$	22	
	Rivet	46-56000	0.5 (u.t.s.)	$\frac{1500000}{\text{u.t.s.}}$		
Structural steel for buildings	Structural	55-65000	0.5 (u.t.s.)	$\frac{1400000}{\text{u.t.s.}}$	22	
	Rivet	46-56000	0.5 (u.t.s.)	$\frac{1400000}{\text{u.t.s.}}$		
Structural steel for locomotives		55-65000	0.5 (u.t.s.)	$\frac{1500000}{\text{u.t.s.}}$		
Structural steel for cars	Structural	50-65000	0.5 (u.t.s.)	$\frac{1500000}{\text{u.t.s.}}$		
	Rivet and flange plates	48-58000	0.5 (u.t.s.)	$\frac{1500000}{\text{u.t.s.}}$		
Structural steel for ships	Structural	58-68000	0.5 (u.t.s.)	$\frac{1500000}{\text{u.t.s.}}$		
	Rivet	55-65000	0.5 (u.t.s.)	$\frac{1500000}{\text{u.t.s.}}$		

* u.t.s. stands for "ultimate tensile strength."

TENSILE PROPERTIES OF VARIOUS STEELS—(*Con.*)

Character and Use of Steel.			Tensile Strength. Lbs. per Sq.in.	Yield Point. Lbs. per Sq.in.	Elongation. Min. in 8 ins. Per Cent.	Elongation. Min. in 2 ins. Per Cent.	Reduction of Area. Min. Per Cent.
Steel Forgings (7 classes of carbon steel forgings are recognized and different specifications are given for each class).*		Lowest grade, untreated material	47-60000	0.5 (u.t.s.)	....	$\frac{1500000}{\text{u.t.s.}}$	$\frac{2500000}{\text{u.t.s.}}$
		Highest quality hardened and tempered	90000	55000	....	$\frac{2100000}{\text{u.t.s.}}$	$\frac{4000000}{\text{u.t.s.}}$
Locomotive and car forgings, hardened and tempered. Axles, shafts, etc.		Max. thickness 4″.	90000	55000	....	$\frac{2100000}{\text{u.t.s.}}$	$\frac{4000000}{\text{u.t.s.}}$
		Thickness 4″- 7″	85000	50000	....	$\frac{2000000}{\text{u.t.s.}}$	$\frac{3800000}{\text{u.t.s.}}$
		Thickness 7″-10″	85000	50000	....	$\frac{1900000}{\text{u.t.s.}}$	$\frac{3600000}{\text{u.t.s.}}$
		Thickness 10″-20″	82500	48000	....	$\frac{1800000}{\text{u.t.s.}}$	$\frac{3400000}{\text{u.t.s.}}$
Locomotive forgings untreated		Max. thickness 8″..	75000	0.5 (u.t.s.)	....	$\frac{1600000}{\text{u.t.s.}}$	$\frac{2200000}{\text{u.t.s.}}$
		Thickness 8″-12″..	75000	0.5 (u.t.s.)	....	$\frac{1500000}{\text{u.t.s.}}$	$\frac{2000000}{\text{u.t.s.}}$
Locomotive forgings annealed.		Max. thickness 8″..	80000	0.5 (u.t.s.)	....	$\frac{1800000}{\text{u.t.s.}}$	$\frac{2800000}{\text{u.t.s.}}$
		Thickness 8″-12″..	80000	0.5 (u.t.s.)	....	$\frac{1725000}{\text{u.t.s.}}$	$\frac{2640000}{\text{u.t.s.}}$
		Thickness 12″-20″..	80000	0.5 (u.t.s.)	....	$\frac{1650000}{\text{u.t.s.}}$	$\frac{2400000}{\text{u.t.s.}}$
Cold-rolled steel axles........................			70000	60000†	....	18	35
Steel castings		Hard.............	80000	36000	....	15	20
		Medium...........	70000	31500	....	18	25
		Soft.............	60000	27000	....	22	30
Boiler and firebox steel		Flange...........	55-65000	0.5 (u.t.s.)	$\frac{1500000}{\text{u.t.s.}}$		
		Firebox...........	52-62000	0.5 (u.t.s.)	$\frac{1500000}{\text{u.t.s.}}$		
Boiler rivet steel...........................			45-55000	0.5 (u.t.s.)	$\frac{1500000}{\text{u.t.s.}}$		
Billet Steel Concrete Reinforcing Bars	Plain Bars	Structural grade....	55-70000	33000	$\frac{1400000}{\text{u.t.s.}}$		
		Intermediate grade..	70-80000	40000	$\frac{1300000}{\text{u.t.s.}}$		
		Hard grade........	80000	50000	$\frac{1200000}{\text{u.t.s.}}$		
	Deformed Bars	Structural grade....	55-70000	33000	$\frac{1250000}{\text{u.t.s.}}$		
		Intermediate grade..	70-85000	40000	$\frac{1125000}{\text{u.t.s.}}$		
		Hard grade........	80000	50000	$\frac{1000000}{\text{u.t.s.}}$		
Cold twisted bars..........................			....	55000	5		
Concrete reinforcing bars from rerolled steel rails		Plain Bars.........	80000	50000	$\frac{1200000}{\text{u.t.s.}}$		
		Deformed bars.....	80000	50000	$\frac{1200000}{\text{u.t.s.}}$		

* See Am. Soc. Test. Matrls. Year-book, 1914.

† Elastic limit, not yield point.

487. Effect of Carbon upon Physical Properties. The distinctive properties of the different grades of ordinary steels, (i.e., not special alloy steels) are due to variations in carbon content more than to any other single factor. Carbon always acts as a hardener and strengthener, but at the same time reduces the ductility.

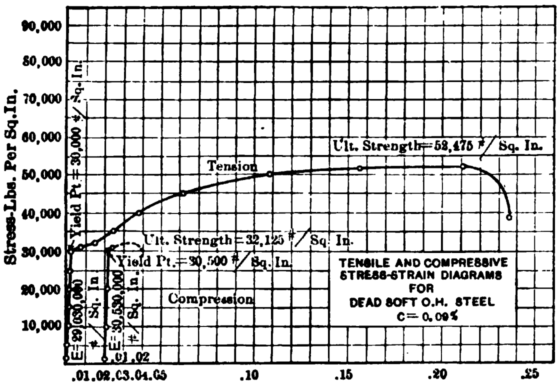

FIG. 252.

The effect of carbon upon the tensile and compressive properties of steels is shown graphically by the series of stress-strain diagrams of Figs. 252 to 261 inclusive. These curves have been plotted from the data of tests made at the Watertown Arsenal.* The steel is in all cases an open-hearth steel, the various test specimens having carbon percentages of 0.09, 0.20, 0.31, 0.37, 0.51, 0.57, 0.71, 0.81, 0.89, and 0.97 per cent respectively. The tensile specimens were 1 inch in diameter and the elongation was measured on a 30-inch gauged length: the compressive specimens were also 1 inch in diameter and were 12 inches long, the compression being measured on a gauged length of 10 inches. It should be noted that the elongations of the tensile specimens appear low only because the long gauged length caused the great extension of the portion of the specimen immediately adjoining the break to have lesser weight in expressing

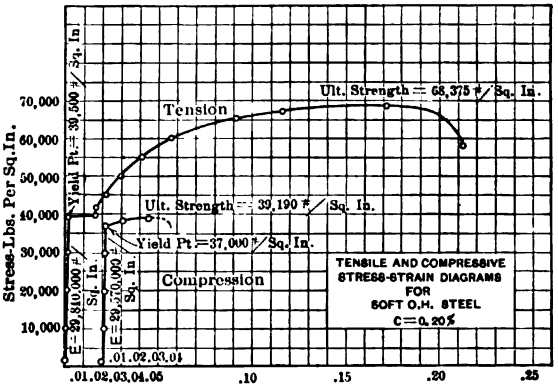

FIG. 253.

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* "Tests of Metals," 1886 and 1887.

the total percentage elongation after fracture, than if this same local extension had been only averaged with the extension of the balance of the length of a standard 8-inch specimen. It should also be noted that the compressive specimens were of such a length, with respect to their transverse dimensions, that failure invariably occurred by triple flexure at a load only slightly above the yield point. If these specimens had been very short, the compressive stress-strain curve would not differ greatly from the tensile curve.

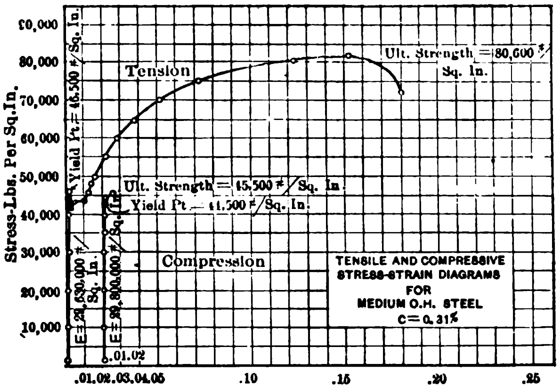


FIG. 254.

The direct relationship between carbon content and tensile strength, as shown by the series of tests above quoted, is summarized in Fig. 262. The relation between ultimate tensile strength and per cent of carbon is expressed with a fair degree of accuracy by the equation:

Ultimate tensile strength = 45,000 + 115,000 (per cent carbon),

and the relation between the yield point and the per cent of carbon is similarly expressed by the equation:

Yield point = 30,000 + 50,000 (per cent carbon).

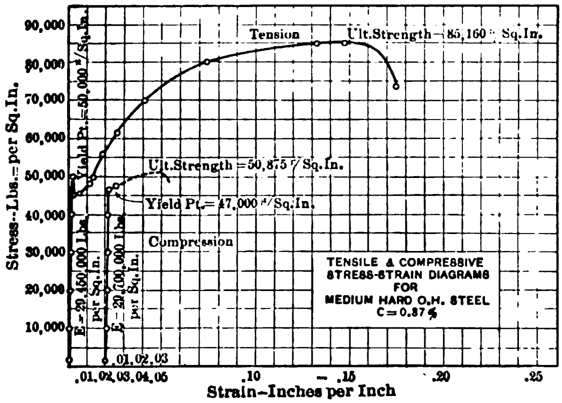


FIG. 255.

The relationship between elongation and ultimate tensile strength, as shown by the same series of tests, is presented by curve *I*, Fig. 263. This same relationship when only a length of 8 inches is considered (the extension of the four 1-inch intervals on either side of the fracture being added and divided

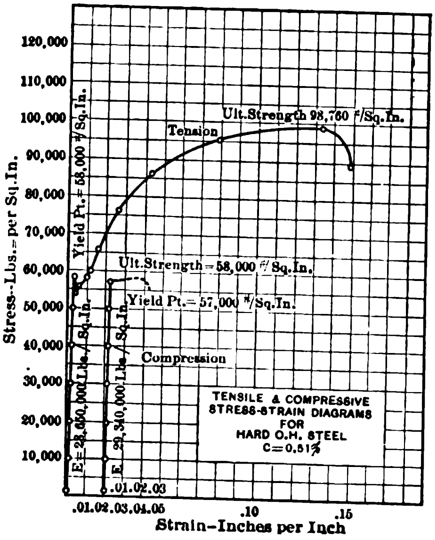


FIG. 256.

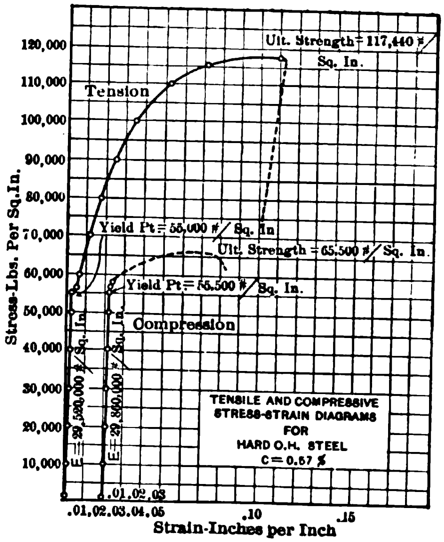
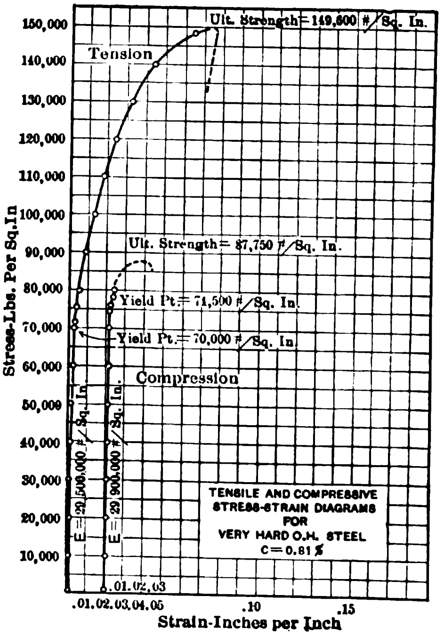


FIG. 257.



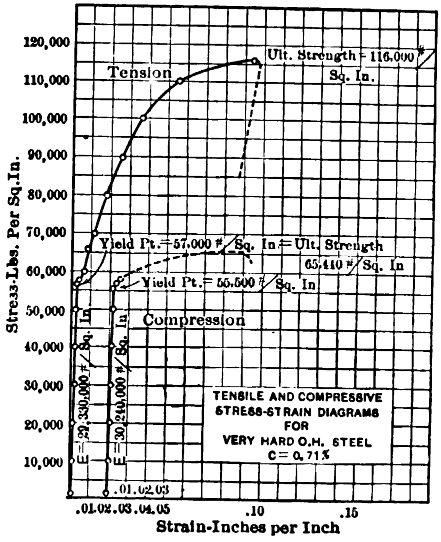


FIG. 258.

FIG. 259.

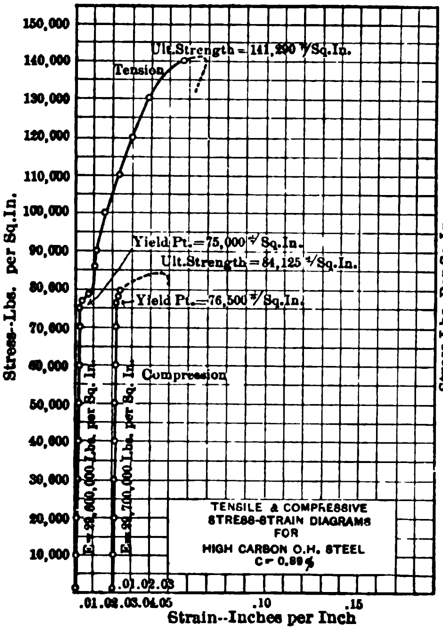


Fig. 260.

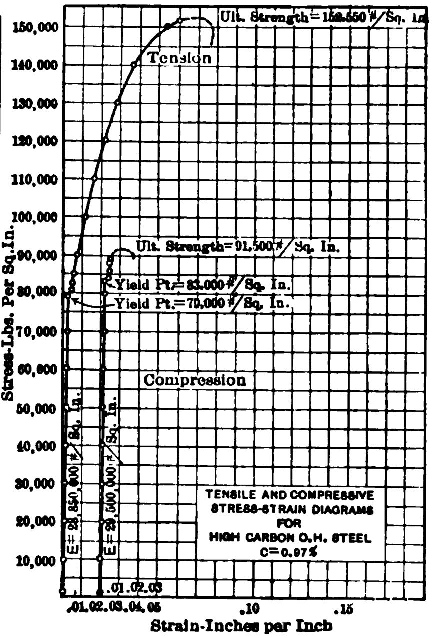


Fig. 261.

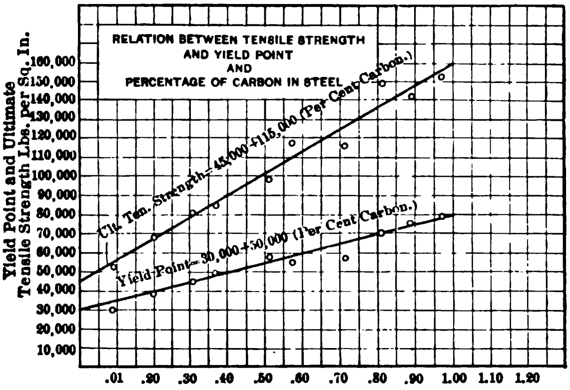


Fig. 262.

by eight) is shown by curve *II*. The equation of this curve is expressed by the formula:

$$\text{Percentage elongation in 8 inches} = 58 - \frac{(\text{ultimate tensile strength})}{2500}.$$

For purposes of comparison curve *III*, which is expressed by the rule given first by a committee of the American Society of Civil Engineers, and used in many specifications, namely:

$$\text{Percentage elongation in 8 inches} = \frac{1{,}500{,}000}{\text{ultimate tensile strength}},$$

is plotted on the same figure.

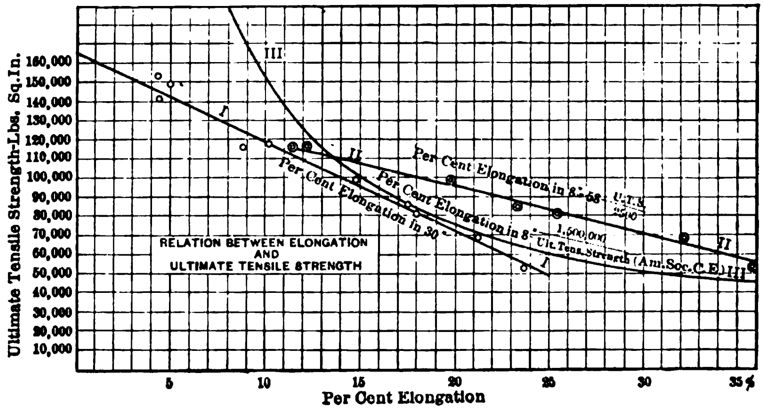


Fig. 263.

The marked effect of gauged length upon percentage elongation above referred to is shown by a comparison of curves *I* and *II*, the former being plotted from the elongation in the entire gauged length of 30 inches, while the latter is based upon the elongation of only a portion of the specimen which was originally 8 inches in length, the portion taken being so chosen that it included the break at its center. This relationship is shown also by the series of curves plotted in Fig. 264, which have been based upon a series of tests of open-hearth steel made by the author. These tests were made upon 1-inch round bars 8 feet long, gauge points having been marked at 1-inch intervals along

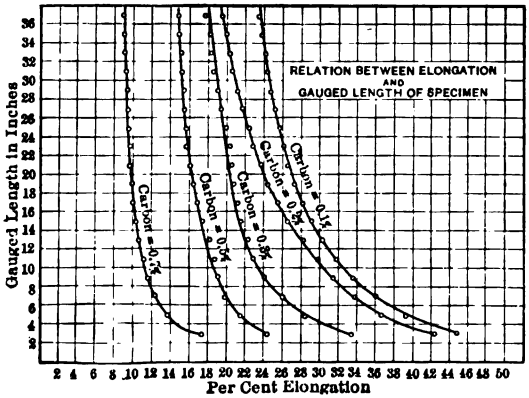


Fig. 264.

the entire length of each specimen. Each of the gauged lengths over which measurements were taken after fracture, included the fracture and necked-down portion at the center, or within ½ inch of the center.

488. Effect of Heat Treatment and Mechanical Working. The effect of hardening, tempering, and annealing of steels upon structure, hardness, and brittleness, has been noted above in Arts. 474 to 478 and and in Art. 483. The effect of the same treatment upon the strength and ductility is best shown by the investigations of Brinell.* The curves shown in Figs. 265 and 266 constitute a summary of a portion of Brinell's experiments. The steel used was an acid open-hearth steel, hot rolled and then subjected to the various heat treatments indicated. The specimens were round bars, 18 millimeters in diameter (0.71 inch), and elongations were measured on a gauged length of 180 millimeters (7.08 inches). The steels were of average high quality and composition in all respects except that the silicon was unusually high. The limits of composition were as follows: Silicon 0.266 to 0.453 per cent (except for the lowest carbon steel, which contained only 0.005 per cent), sulphur 0.01 to 0.02 per cent, phosphorus 0.025 to 0.030 per cent, and manganese 0.01 to 0.49 per cent. A study of the curves leads to the following conclusions:

Annealing at 350° C. has little effect upon the strength of low- and medium-carbon steels, but increases the strength of high-carbon steels slightly; the ductility of all steels is increased slightly.

Annealing at 750° C. has little effect upon the strength of low- and medium-carbon steels, but decreases the strength of high-carbon steels slightly; the ductility of all steels is increased considerably.

Annealing at 850° C. has little effect upon the strength of any class of steel, but increases the ductility considerably, particularly the high-carbon steels.

Annealing at 1000° C. has practically no effect upon the strength of low- or medium-carbon steels, but slightly increases the strength of high-carbon steels; the ductility of all steels is increased slightly, the low-carbon steels more particularly.

Water quenching at 750° C. increases the strength of low-carbon steels greatly, medium-carbon steels slightly, and scarcely affects the strength of high-carbon steels; the ductility of low-carbon steels is reduced very greatly, medium-carbon steels slightly, and high-carbon steels are scarcely affected at all.

Reheating to 550° C., after water quenching at 750° C. restores the steel to practically its original strength in all cases; the ductility is in every case very much greater than that obtained after quenching, but

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* Journal of the Iron and Steel Institute, 1901.

is only slightly greater than that obtained with the steel in its original condition.

Water quenching at 850° C. increases the strength of low-carbon and medium-carbon steels very greatly, but scarcely increases the strength of high-carbon steels because of the increased brittleness; the ductility is reduced enormously for the low- and medium-carbon steels and is practically zero for high-carbon steels.

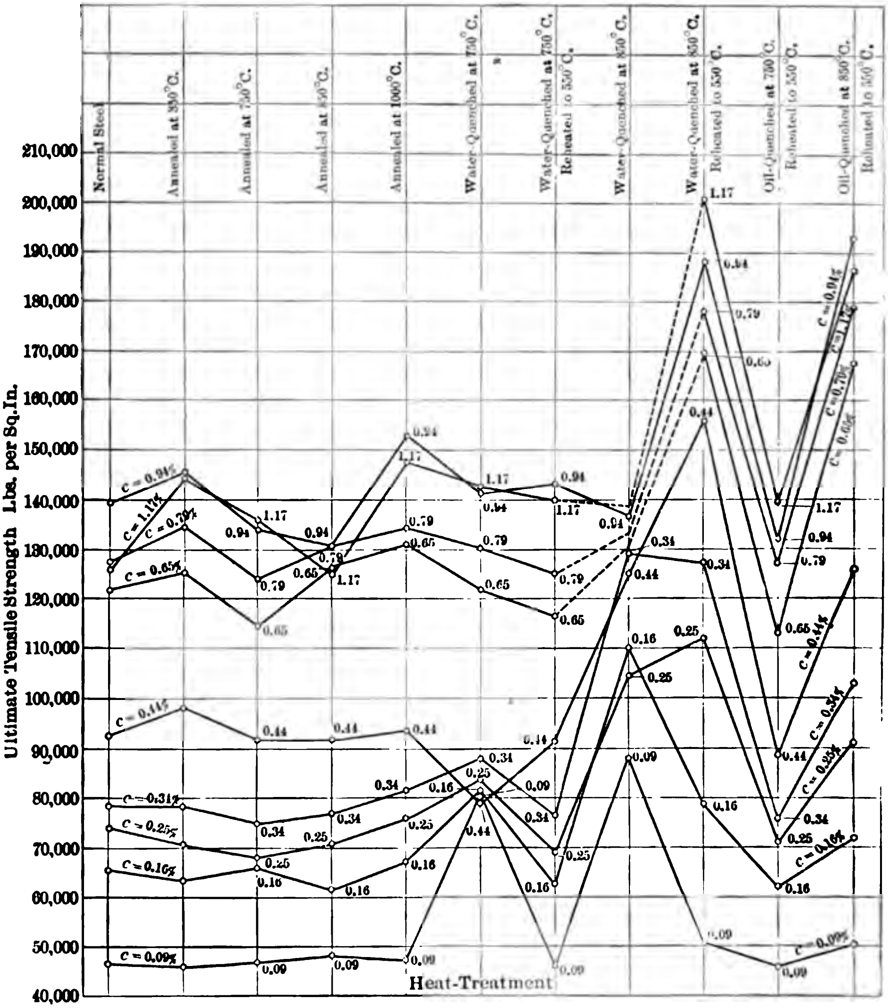

Fig. 265.—Effect of Various Heat Treatments upon Tensile Strength of Various Steels.

Reheating to 550° C. after water-quenching at 850° C. largely nullifies the gain in strength of low- and medium-carbon steels caused by quenching, and enormously increases the strength of high-carbon steels by removing brittleness; the ductility is restored to practically its original value before quenching.

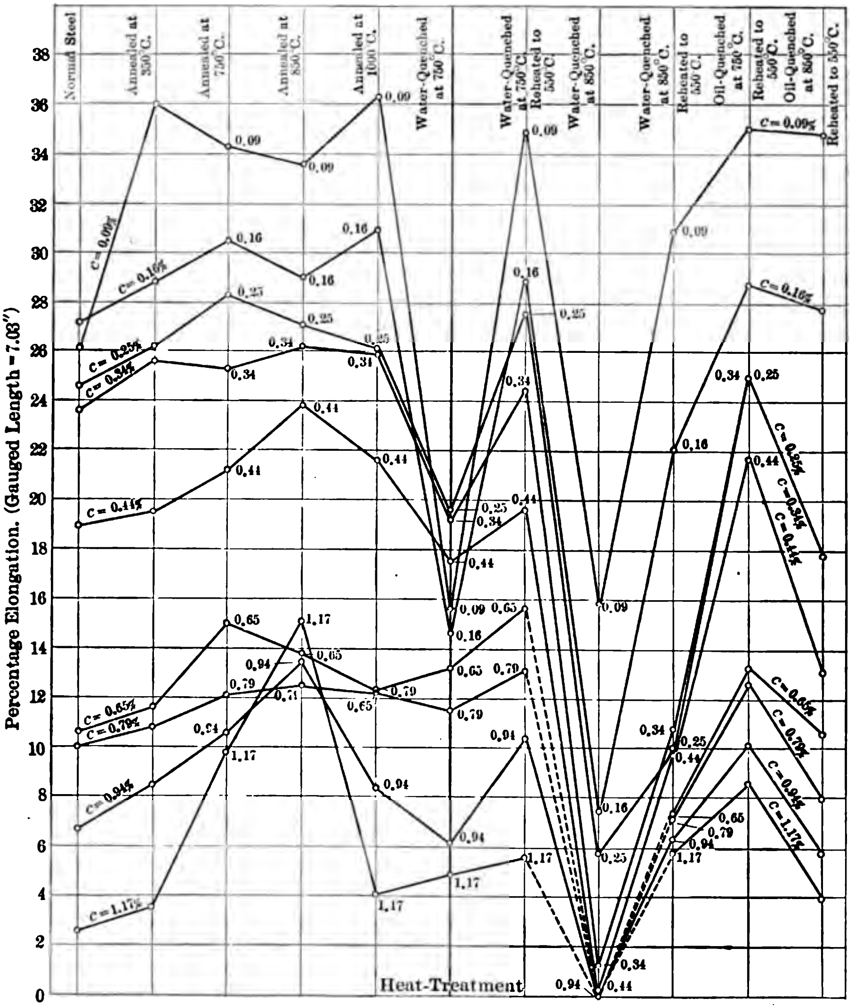

FIG. 266.—Effect of Various Heat Treatments upon Elongation of Various Steels.

Oil quenching at 750° C. followed by reheating to 550° C., has little effect upon the strength of any class of steel, but increases the ductility of low- and medium-carbon steels slightly, and high-carbon steels considerably.

Oil quenching at 850° C. followed by reheating to 550° C., increases the strength of all except the very low-carbon steels remarkably; the ductility of any grade of steel is not materially affected.

The effect of hot mechanical working upon the structure and characteristics of steels has been mentioned in connection with the discussion of rolling, hammering, and pressing of steel. The first effect of working is the benefit derived from the elimination of flaws, blow-holes, etc., which become closed up. The coarse crystalline structure of steel slowly cooled from a high temperature is also improved by working, since the crystals become broken up, mixed intimately, thus destroying the continuity of their cleavage planes, and compacted together, thus increasing both their cohesive and their adhesive power.

The amount of reduction necessary in rolling or forging the finished section from the ingot is dependent on many variable factors. It is a fact recognized in the ordinary practice of steel mills, however, that the finished section should never be more than 10 per cent of the ingot section, and it is commonly not more than 2 or 3 per cent, often being much less than 1 per cent.

The temperature at which working is finished is a very important consideration, since, if this temperature is above a red heat, the crystals grow to a certain extent, thus diminishing strength and especially lowering the elastic limit of the steel. In the ordinary practice of rolling structural steel the finishing heat is above the red heat and the elastic limit is therefore comparatively low. If the working be continued until the metal is not above a dull red heat the material is immobile, large crystals cannot reform, and strength and especially the elastic limit are greatly increased.

Cold working of steels, i.e., the mechanical distortion of the metal below the critical range of temperatures, cannot be practiced except with low- or medium-carbon steels, because high-carbon steels are too deficient in ductility and too brittle to be worked below the critical range. The effect of cold working upon the existing structure (made up of pearlite with free ferrite) is simply to elongate the crystalline elements in the direction of working. Cold working does not improve the crystalline structure as does working above the critical range, and the primary effect of cold working upon physical properties is a marked decrease in ductility and increase in brittleness. One other effect which constitutes a great practical advantage in the case of steels used for certain purposes, is the very material extent to which the elastic limit of steel may be raised by cold working. This fact is taken advantage of in the manufacture of certain grades of hard wire (unannealed after completion of the drawing process), and in the finishing of steel rods intended for particular purposes such as concrete reinforcement. In the latter case the cold distortion of the metal by special rolls which deform the bars and produce alternate depressions and elevations, or by cold twisting of square bars, is commonly practiced. The purpose of such distortion is primarily to increase the hold of concrete on the steel by providing a mechanical bond, but this purpose could more cheaply be served by hot working were not the distinct advantage gained by cold working recognized. The extent of the effect of cold working is directly dependent upon how far below the critical range working is continued, and is most marked when working is done at atmospheric temperatures.

489. Effect of Silicon, Sulphur, Phosphorus, and Manganese. The direct effect of silicon, in the ordinary proportions commonly encountered in steels (usually not over 0.2 per cent), upon strength and ductility is very slight. Whatever effect there may be is difficult to determine, because it is masked by the influence of other elements, like carbon and phosphorus, which cannot be made to be altogether constant factors, and which are much more influential in this respect. Increasing the silicon content intentionally to 0.3 or 0.4 per cent has the effect of raising the elastic limit and ultimate strength of the steel considerably, without reducing the ductility greatly. This is sometimes done in the production of steel castings. Special silicon steels containing over 1.0 per cent of silicon will be mentioned later.

Sulphur, within the limits common to ordinary steels (0.02 to 0.10 per cent) has no appreciable effect upon the strength or ductility of steels. It has, however, a very injurious effect upon the properties of the hot metal in lessening its malleability and weldability, thus causing difficulty in rolling called "red-shortness." If it were possible that the steel might contain an excess of sulphur over that which is neutralized by manganese, the effect would certainly be to reduce both strength and ductility. Specifications for structural steels commonly limit the sulphur content to a maximum of from 0.04 to 0.05 per cent.

Phosphorus is the most undesirable of all the elements commonly found in steels. Its effect upon the properties of steels is very capricious, but it is always detrimental to toughness or shock-resistance, and often detrimental to ductility under static load. Campbell states that the strength of steel under static load is increased by 1000 pounds per square inch for each 0.01 per cent of phosphorus so long as the total phosphorus does not exceed 0.12 per cent. Beyond this limit even static strength is diminished. Phosphoric steels are apt to break under very slight stress if this stress is suddenly applied or if vibration is encountered, and this fact alone is sufficient to bar phosphoric steels from most uses in construction. The loss of ductility, due to increased brittleness, is not always noted in tests of high-phosphorus steels, and it is therefore difficult to detect the presence of too high phosphorus by the ordinary methods of mechanical testing. Specifications commonly limit the phosphorus content of structural steels to a maximum of from 0.04 to 0.06 per cent.

Manganese is an element which is commonly comparatively high in most steels because of the prevalent practice of using either spiegeleisen or ferro-manganese as a recarburizer and deoxidizer in the Bessemer and open-hearth processes. The effect of manganese upon the properties of steel is a rather involved question, but it has a tendency to increase the strength provided a certain limit is not exceeded. If this limit is exceeded its effect in the direction of increasing brittleness causes a reversal of its effect upon strength. With less than 0.3 or 0.4 per cent manganese the steel is apt to be impregnated with oxides whose harmful effect outweighs any beneficial effect due to the manganese. Between 0.3 or 0.4 per cent and about 1.5 per cent manganese, the beneficial effect is dependent upon the amount of carbon present. With 0.1 per cent of carbon (according to Bradley Stoughton), the strength is increased about 100 pounds per square inch for each 0.01 per cent of manganese over 0.3 or 0.4 per cent; with 0.2 per cent carbon, the gain is about 165 pounds per square inch for each 0.01 per cent of manganese; and with 0.4 per cent of carbon the gain is about 280 pounds per square inch for each 0.01 per cent of manganese. In all cases the beneficial effect is somewhat more marked with acid than with basic steel. As the content of manganese rises above 1.5 or 2.0 per cent the metal becomes so brittle as to be worthless, but as the content of manganese is further increased a curious reversal takes place with about 6 or 7 per cent of manganese. The properties of this special manganese steel will be discussed later under the head of special or alloy steels.

490. Shearing Strength. Direct Shear. Torsion. The shearing strength of steel is dependent to a very large extent upon the same factors as the tensile and compressive strength. It is therefore to be expected that a more or less constant relation may be found between the shearing strength and the tensile strength. Experiments have amply demonstrated that such a relationship does exist, and have further shown that the value of the factor for most grades of steel is about 0.8, i.e., the shearing strength is about eight-tenths of the tensile strength. This fact is well shown by the appended table abstracted from the tests of Prof. A. B. W. Kennedy:*

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* Proc. Inst. of Mech. Engrs., 1885.

RELATION BETWEEN SHEARING AND TENSILE STRENGTH

Kind of steel	Ult. Tens. Strength Lbs. per Sq.in.	Shearing Strength Lbs. per Sq.in.	Ratio
Open-hearth	57,000	47,500	0.83
" "	63,500	51,000	0.80
" "	64,000	52,000	0.81
" "	69,000	56,000	0.81
Bessemer (hard)	71,000	51,000	0.72
" "	78,000	64,000	0.82
" "	82,000	59,000	0.72
" "	118,000	79,000	0.67

Torsional stresses are nothing more than shearing stresses which, instead of being confined to a single section or a limited number of isolated sections of a specimen or part of a structure or machine, are common to every section between the planes of the external forces which produce the twisting moment called the torque. The intensity of the shearing stress on any section of a shaft is not uniform, however, but varies directly as the distance from the axis of the shaft (considering that the section is circular), and the maximum intensity of shearing stress is therefore found at the circumference. The mathematical expression for the maximum shearing stress in the extreme fiber of circular shafts is:

$$s_1 = \frac{2Pa}{\pi r^3},$$

(wherein *Pa* is the torque, *r* is the radius of the section, and s_1 the shearing stress in the extreme fiber of the shaft), and the shearing modulus of elasticity is expressed by the equation

$$E_s = \frac{s_1 l}{r\theta},$$

(wherein *l* is the distance between the planes of the external forces, and θ is the angle of torque or twist).

From the following table, which is a summary of a series of tests made by the author, it will be noted that the shearing strength as determined by torsion tests appears higher than it does in the case of direct shear. This is due to the fact that the expression for s_1 above is true only as long as the material behaves elastically. When computed for the torque which produces rupture it is called the "torsional modulus of rupture" and corresponds to the true value of the shearing strength of the material only as the modulus of rupture corresponds to the actual extreme fiber stress. (See Art. 374.)

Upton * has shown that a definite relation exists between the shearing modulus of rupture and the direct shearing strength, the relation being that expressed by the graphical construction shown by Fig. 267. On this diagram the curve *OEA* expresses the relation of torsional shearing stress to torsional strain and is the usual form of graphical representation of a torsion test. The dotted line which represents the direct shearing stress (the true shearing stress in the extreme fiber of the torsion specimen also), is obtained by the following construction: At any point *A* on the curve draw a tangent and prolong same to its intersection with the axis *OB*. Lay off from *A* a distance *AA'* equal to $\frac{1}{4}$ *OB*. The point *A'* will lie on the curve of true or direct shearing stress, as Upton has shown by mathematical analysis. The curve *EA'* may thus be constructed point by point.

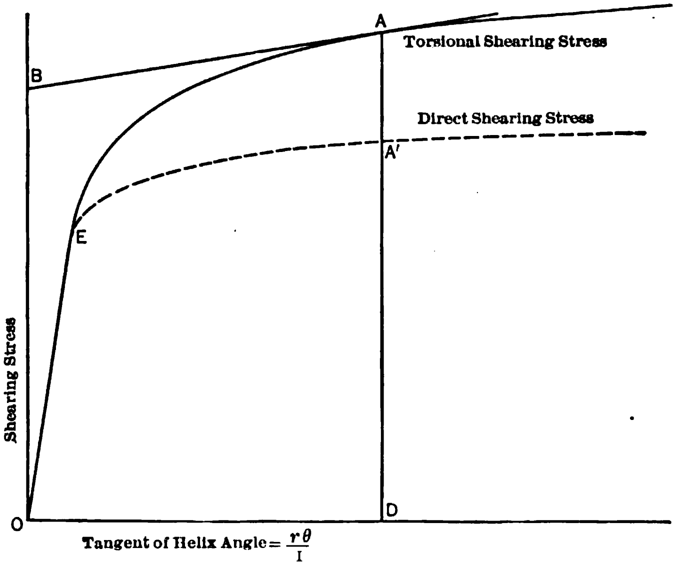

FIG. 267.—Relation between Torsional and Direct Shearing Stress. (Upton.)

The most significant fact illustrated by this diagram is that as the latter portion of the curve becomes more and more nearly flat the ordinates to the curve of true shear become more and more nearly equal to three-fourths the corresponding ordinates of the torsional shear diagram, so that the true shearing strength of steel (or any ductile material) is practically equal to three-fourths the value of the torsional modulus of

* G. B. Upton. "The Sibley Journal of Engineering," June, 1913.

rupture. This fact is of value, because torsion tests are much more easily made than are direct-shear tests.

STRENGTH OF STEEL IN TORSIONAL SHEAR

Class of Steel	Computed Extreme fiber Stress Lbs. per Sq.in.	Shearing Mod. of Elasticity Lbs. per Sq.in.	Number of Complete Turns per Ft. of Length	Number of Tests Averaged
Mild Bessemer.......	64,200	11,320,000	2.28	15
Medium Bessemer ...	68,300	11,570,000	2.26	10
Hard Bessemer	74,000	11,700,000	2.01	10
Cold-rolled..........	79,900	11,950,000	1.81	12

491. Transverse Strength, Flexure and Deflection. The transverse strength of steel is directly dependent upon the tensile and compressive properties of the metal, for failure in cross-bending must necessarily occur either through failure of the loaded side of a beam in compression or by failure of the opposite side in tension. Whether the former or the latter is the controlling factor is dependent upon the form of the beam and the location of the neutral axis. If the section is symmetrical the failure will usually occur on the tension side if the steel is not a ductile grade, and on the compression side (when the maximum compressive stress has only just exceeded the yield point) if the steel is a ductile grade. Absolute rupture in cross-bending is not possible with any grade of mild or medium steel, since these steels may be bent 180 degrees flat without fracture. Some cast steels and most high-carbon steels may be actually ruptured.

The modulus of elasticity of steel in bending is exactly the same as in tension and, since the flexure, and consequently the deflection, is inversely proportional to the value of E, the deflection of all steels within the limits of load which do not stress the most stressed fiber beyond its elastic limit will be practically the same. (We assume that the section, the span, and the value of I are constant.) The maximum deflection attainable at the time of failure will be quite variable, however, even when I is constant, because it is dependent upon the yield point and the ductility of the steel.

492. Effect of Combined Stresses upon Elastic Properties. The situations in machines and in structures where steel members are subjected to a combination of stresses of different characters are so commonly encountered that the problem of the resultant elastic properties of the material becomes one of great practical importance. The following specific cases are merely illustrative of the great number of instances of a combination of stresses which might be cited:

A steel rivet transmitting load between the two members of a riveted connection is subjected to shearing stress, which is combined with tension caused by its longitudinal contraction after having been driven hot; a steel pin which holds together the various members of a pin-connected truss which meet at a joint, is subjected to a combination of shearing and bending stresses; a power transmission shaft which carries driving pulleys between the shaft hangers is subjected to combined torsion, flexure, and direct shear; a steel wire-rope power transmission is subjected to combined tension and flexure; a non-rectilinear strut is subjected to combined compression and flexure; shearing stresses practically never occur in members of structures or machines without being combined with flexure, etc., etc.

Probably the most extensive study of the effect of combined stresses upon the resultant elastic properties of steels is that made by Mr. E. L. Hancock at Purdue University,* although important investigations have been made by others, notably those of Mr. J. J. Guest † and those of Mr. W. H. Scoble.‡

Hancock's results are summarized by Figs. 268, 269 and 270. The curves represent the following series of tests:

(*a*) Tension tests of steel rods while under various fixed torsional stresses.

(*b*) Torsion tests of steel rods while under various fixed tensile or compressive stresses.

(*c*) Tension tests of steel tubes while under various fixed torsional stresses.

(*d*) Compression tests of steel tubes while under various fixed torsional stresses.

(*e*) Flexure tests of steel shafts while under various fixed torsional stresses.

(*f*) Shearing tests of steel rivets while under various fixed tensile stresses.

From Fig. 268 it appears (1) that the elastic limit of steel in tension, compression, or flexure is lowered by the coexistence of torsional stress, the amount of lowering of the elastic limit being proportional to the magnitude of the torsional stress relative to the torsional elastic limit. (2) The elastic limit of steel in torsion is similarly lowered by the coexistence of either tensile or compressive stress.

Mr. Hancock found that a torsional shear in the extreme fiber of a

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* Proc. Am. Soc. Test Matrls., Vol. 5, p. 179; Vol. 6, p. 295; Vol. 7, p. 258; Vol. 8, p. 373; and Vol. 9, p. 427.

† Proc. Physical Soc. of London, Sept., 1900.

‡ Philosophical Magazine, Dec., 1906.

shaft or tube equaling the elastic limit in torsion lowered the elastic limit of the steel in flexure about 28 per cent, in compression about 42 per cent, and in tension about 50 per cent. A torsional stress of lesser magnitude lowered the elastic limit in each case proportionally. Conversely, he found that a tensile or compressive stress equal to the elastic limit in tension or compression, respectively, lowered the elastic limit in torsion about 79 per cent.

From Fig. 269 it appears (1) that the strain at the elastic limit in tension or compression is lowered by the coexistence of torsional stress, but not as much proportionally as the corresponding stress, this meaning therefore that the modulus of elasticity is slightly lowered, (2) the deflection at the elastic limit in flexure is lessened by the coexistence of torsional stress, and the relative effect upon this deflection and the corresponding stress at the elastic limit is such that the modulus of elasticity in flexure is also slightly lowered.

From Fig. 270 it appears (1) that the shearing strength of rivet steel is reduced about 12 per cent if it is at the same time stressed to its elastic limit in tension, and (2) that the shearing elastic limit is reduced about 33 per cent under the same conditions. The lowering of the strength and elastic limit in shear by a coexistent tensile stress below the tensile elastic limit appears again to bear a relation to that above noted nearly proportional to the ratio of the existent tensile stress to the tensile elastic limit.

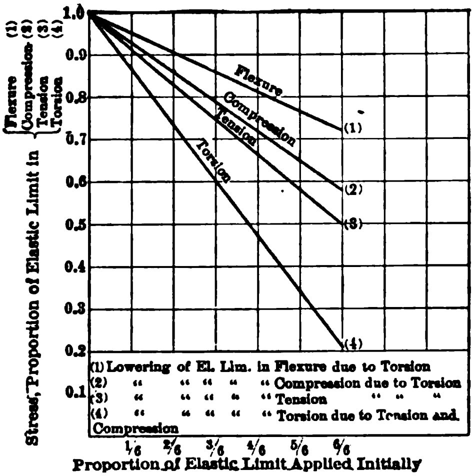

Fig. 268.—Effect of Combined Stresses upon Elastic Limit of Steels.

493. Hardness of Steels. The precise meaning of the term hardness as applied to metals is, as above stated, Art. 366, not altogether fixed. Hardness referring to machine cutting tools means the ability to hold an edge while cutting metal; with respect to steel rails and the tires of car wheels it means the resistance to dry rolling friction; applied to the tires of locomotive drivers the term involves dry rolling friction combined with slippage; applied to axles and bearings it means resistance to wear

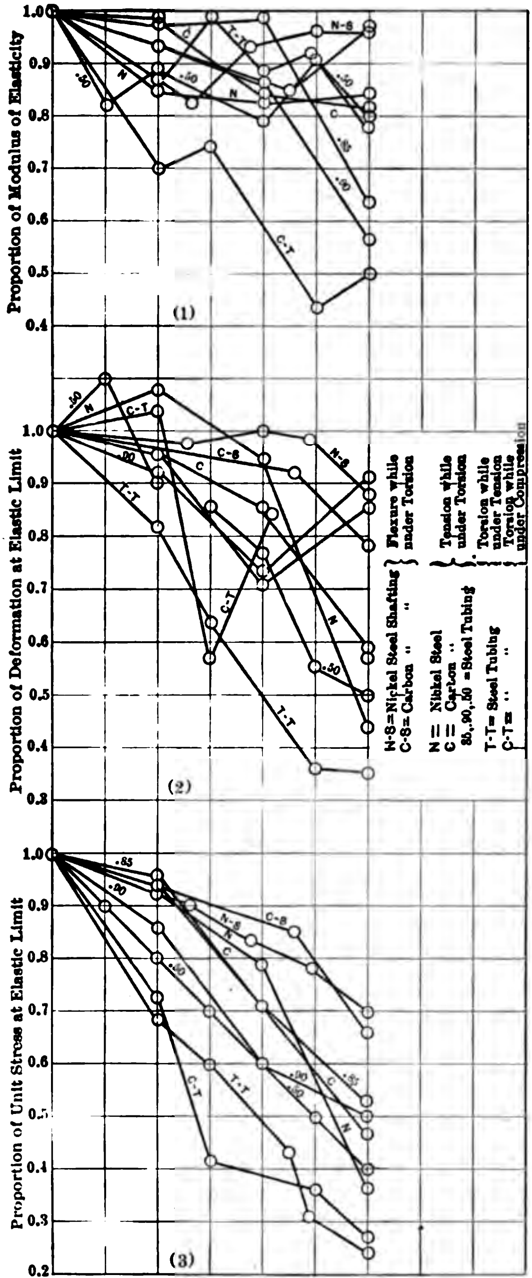

FIG. 269.—Effect of Combined Stresses upon (1) Modulus of Elasticity; (2) Deformation at Elastic Limit; (3) Unit Fiber Stress at Elastic Limit.

between lubricated surfaces; respecting the performance of gears it means not only frictional wear between lubricated surfaces, but also involves toughness; the hardness of the crushing faces of rock-grinding machinery is a measure of resistance to combined abrasion and shock; the hardness of machinery steel is a measure of the difficulty experienced in cutting or machining it, etc., etc.

Properly, the toughness and resiliency of steel are properties distinct from hardness, and resistance to wear is quite a different thing from resistance to cutting or indentation, but as will be shown by the following consideration of methods of hardness measurement, the term hardness is used meaning any or all of these things.

(1) The *Brinell* method is based upon determining the resistance offered to indentation by a hardened sphere, the latter being subjected to a given pressure. Brinell expressed the hardness by the pressure in kilograms per square millimeter of spherical area of indentation. Origi-

nally the spherical area of indentation was computed upon the assumption that the radius of curvature of the indentation is equal to the radius of the sphere used. This method was shown by several investigators to be in error, owing to the fact that the sphere flattens slightly under pressure, thus causing the radius of indentation to exceed that of the sphere. In consequence non-concordant values of the hardness numeral were obtained in using spheres of different diameters, or in employing different pressures, in investigations of the hardness of different materials. When the area of indentation is computed upon the basis of its actual radius of curvature, however, this disturbing factor is eliminated and the results obtained by the Brinell test are truly comparable and of great practical value.

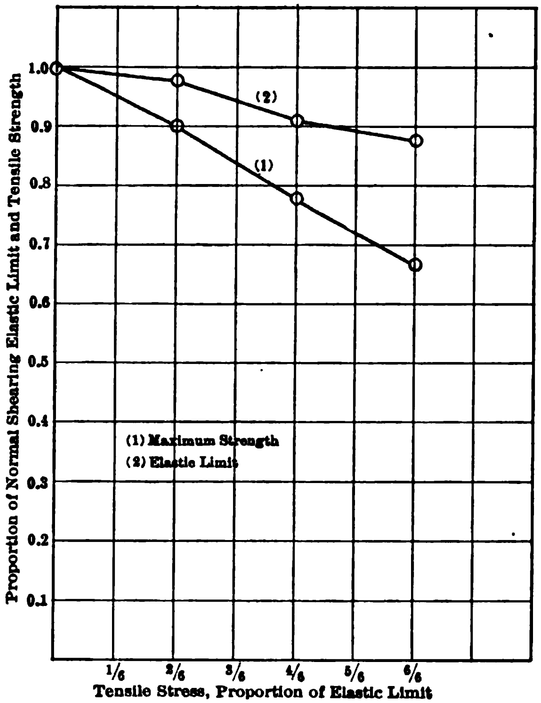

FIG. 270.—Effect of Tensile Stress upon Shearing Elastic Limit of Rivet Steel.

The fact that the hardness numerals by the rule $\Delta = \frac{P}{a}$ (Δ = hardness numeral, P = pressure in kilograms, and a = area in square millimeters of the spherical impression) are referred to diameters of the impressions by the law of reciprocals, has been taken advantage of by M. Guillery,* who has expressed the relation by a straight line on a diagram having logarithmic coordinates, Fig. 271. The ordinates on this diagram are diameters of the impression produced by either a 10-millimeter ball under 3000 kilograms load (scale at left of diagram) or a 5-millimeter ball under 750 kilograms load (scale at right of diagram). The corre-

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* Proc. Sixth Congress of International Association for Testing Materials, 1912. Paper III5.

sponding hardness numerals (for either scale of diameters, the relation of load to diameter of sphere remaining constant) are plotted as abscissae.

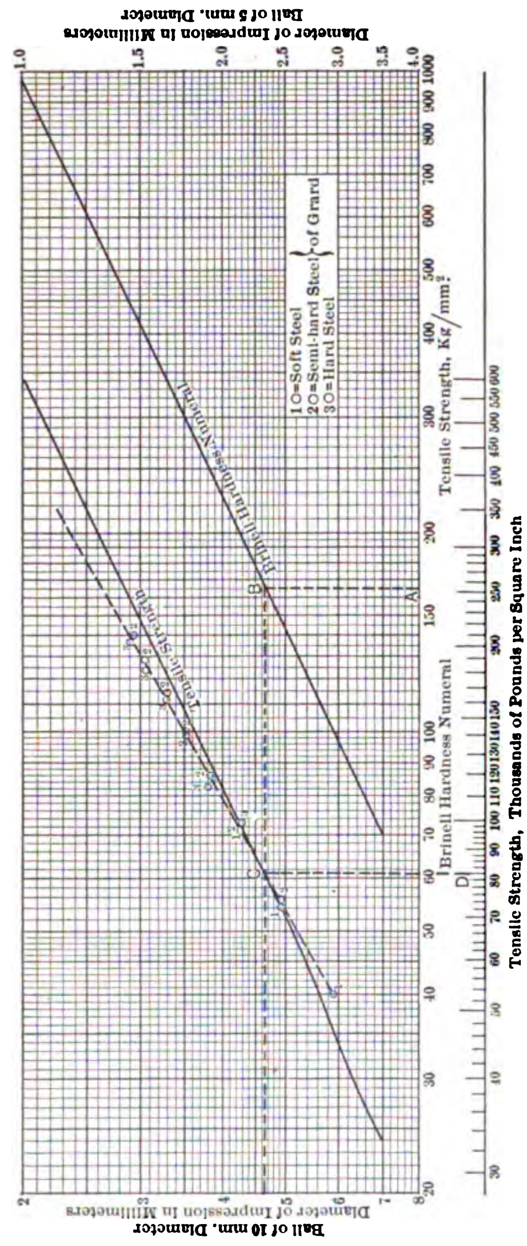

FIG. 271.—Relation of Hardness to Tensile Strength. (After R. Guillery, C. le Chatelier, and C. Grard.)

The relation of hardness (as expressed by the Brinell number) to tensile strength is also shown by the diagram of Fig. 271. The curve of tensile strength is based upon the tests made by Messrs. Guillery and le Chatelier. The manner of application of the diagram will be made clear by the following example:

Suppose the measured diameter of the impression made by the 10-millimeter ball is 4.63 millimeters, the corresponding Brinell hardness numerical is then about 165, as is indicated by the line *BA*, and the corresponding tensile strength is about 61 kilograms per square millimeter, or 82,000 pounds per square inch as indicated by the line *CD*. (The author has added the scale of tensile strength in English units to Guillery's diagram.)

From the fact that the curve of tensile strength is nearly a straight line it appears from the tests of Guillery and le Chatelier that the relation of the Brinell hardness number to tensile strength is a nearly constant relation. The same relation is shown for a series of hardened carbon steels, variously tempered, by the curves of Fig. 272, which has been based upon tests made by M. Grard.* It will be noted that the relation of hardness to tensile strength and elastic limit is remarkably constant for this entire series of steels, which includes a wide range from very soft to very hard grades. For purposes of comparison Grard's results have been plotted by the author on Guillery's diagram, as has been indicated on Fig. 271. The dotted line averages Grard's results. It appears that slightly different curves represent the relation of hardness to tensile strength in the case of the steels used by Guillery and the hardened steels used by Grard.

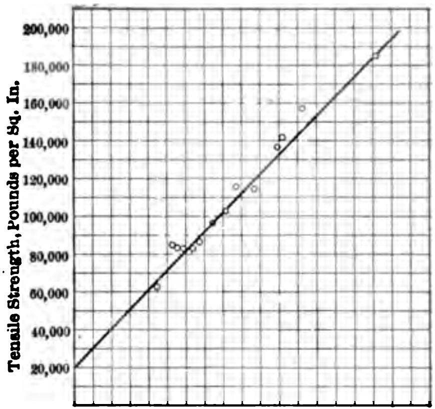

FIG. 271*a*.—Relation of Hardness to Tensile Strength. (Devries.)

The relation between Brinell hardness and ultimate tensile strength has recently been presented by Devries † in the very convenient form expressed by Fig. 271 (*a*). This figure is based upon tests of a series of sixteen steels comprising low-, medium-, and fairly high-carbon steels, also nickel steels, nickel-chrome steels, and chrome-vanadium steels.

The ultimate strength, computed (on the basis of the relation shown by Fig. 271 (*a*), from the hardness numeral, does not in the case of any individual steel depart from the value found in the tensile test by more than about 7 per cent, and only in the cases of two steels did this error amount to more than 5 per cent.

The equation of the curve of Fig. 271 (*a*) is,

$$\text{Ultimate strength} = 20{,}000 + 103.2 \text{ (Devries' hardness numeral).}$$

It appears therefore that the ultimate strength of a steel may be foretold to a very reasonable degree of accuracy by making the hardness test and applying the above rule.

* Proc. Sixth Congress of Internat. Assoc. for Testing Materials, 1912, paper III2.

† Proc. Sixth Congress, Internat. Assoc. Test. Matrls., New York, 1912, p. IX2.

Attention should be called to the fact that Devries does not use the Brinell hardness numeral, but expresses the hardness by the load in kilograms required to produce an indentation 0.1 millimeter deep. In a previous investigation * Devries had established the fact that the load applied to the Brinell sphere and the depth of impression produced are directly proportional.

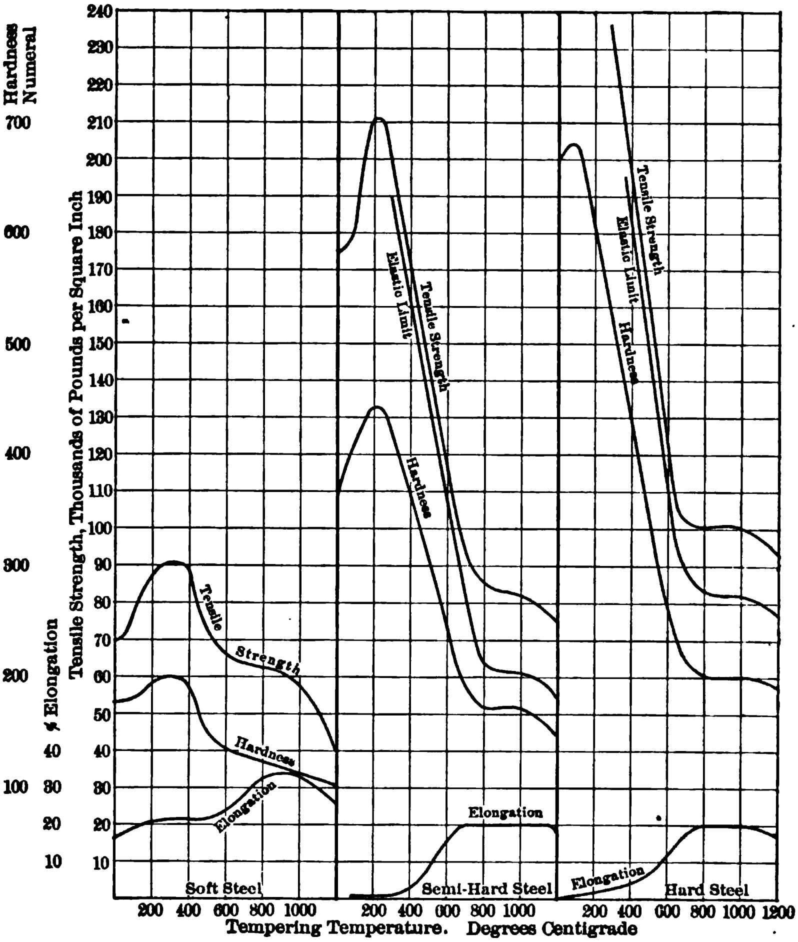

FIG. 272.—Relation of Hardness (Brinell Test) to Tensile Properties (Grard).

(2) The *cone test*, first proposed by Ludwick,† is the same in principle as the Brinell test, but a hardened steel cone of 90° angular opening

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* Proc. Am. Soc. for Test. Matrls. Vol. 11, 1911, p. 709.

† " Die Kegelprobe. Ein neues Verfahren zur Hartebestimmung von Materialen."

is substituted for the steel sphere. The hardness numeral is computed on the basis of the pressure divided by the area of the conical indentation. The relation between the load and the hardness numeral thus obtained is not a constant or straight-line relation, but is a parabolic relation. The hardness scale obtained by the cone test is therefore not a uniform scale. The cone test fails on very hard steel because of the flattening of the point of the cone under the heavy pressure required.

(3) *The Shore scleroscope test* * is made by the use of a pointed hammer which is allowed to fall through a guiding glass tube upon the metal being tested. The hardness is expressed by the height of rebound of the hammer after falling from a specified height. The hammer of the instrument becomes slightly changed in form after a certain number of tests and must then be recalibrated. The indications of the instrument must certainly be dependent in some measure upon the resiliency of the material tested as well as that of the hammer itself, but the extent of the permanent deformation of the metal is also a factor. Perhaps a definite relation exists between resiliency and hardness as measured by indentation. At any rate fairly parallel results are obtained by the Brinell method and the scleroscope method.

(4) *The Bauer drill test* is made by the use of a special drill driven at constant speed with a fixed pressure of the drill upon the specimen of steel. The hardness is measured by the depth of the hole drilled with a given number of revolutions, the pressure remaining constant. This test is of course simply a measure of the resistance offered to cutting. Its applicability is limited to comparatively soft steels or other metals softer than hardened carbon steels or hard alloy steels. Its range of usefulness on comparative tests is rather limited, owing to the fact that the pressure and the rate of revolution must be changed if the metals tested are of greatly different characters.

(5) Tests of the resistance of steel to wear caused by dry rolling friction have been made by Norris † with a machine which utilizes three case-hardened rollers between which a cylindrical specimen is placed. Two rollers are gear driven at slightly different rates of speed, while the third roller is revolved by traction on the specimen. The pressure exerted by the third roller on the specimen is subject to control, and is measured by a dynamometer arrangement. The specimen is thus subjected to rolling and slipping action in a manner which is considered comparable to the action of locomotive drivers on rails, etc. The resistance to wear is expressed by the loss in weight of the specimen after a certain number of revolutions at a constant speed and pressure. The results

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* Proc. Am. Soc. Testing Materials, Vol. 10, p. 490.

† Proc. Am. Soc. Testing Materials Vol. 13, p. 562.

of this test do not agree at all closely with the hardness determination made by the Brinell or scleroscope methods, as is in fact to be expected, since the resistance of a material to wear is a quite different property from its resistance to indentation or its resiliency.

In concluding the discussion of hardness of steels and the various methods of measuring hardness, it may be remarked that the hardness test has come into much more general favor in Europe than it has in the United States. Even in this country, however, it is finding a constantly widening field of application, and the time appears to be not far distant when it will be generally used as a test of castings, hardened steels which are too brittle to be tested satisfactorily in tension, and alloy steels and alloys in general. The hardness test (particularly the Brinell test) possesses the great advantage over the tension test of not requiring a special test piece. It can be used, in fact, to test articles like castings, forgings, etc., without impairing their subsequent availability for use. It can also be used advantageously in exploring different portions of a finished article to ascertain the varying effect of cooling conditions, working, etc., upon the character of the metal.

494. Ductility of Steels as Indicated by Cold Bending. The indication of the ductility of steel which is afforded by a simple cold-bending test is very valuable and significant, and the test possesses the advantage of being one which can easily be made without special appliances. Cold-bending is accomplished either in a vise, or an anvil, or with a steam hammer or hydraulic press. According to the severity of the test desired the bend may be made over a sharp edge, or about a pin or template of any desired radius. The relative extent to which various classes and grades of steels are expected to stand cold-bending is indicated by the following summary of the specifications of the American Society for Testing Materials:*

STANDARD SPECIFICATIONS FOR COLD-BENDING TESTS OF VARIOUS STEELS.

Character and use of Steel.		Cold Bend.*
Rail splice-bar steel	Low carbon	180° d = 0
	Medium carbon	180° d = 2t
	High carbon	90° d = 3t
	Extra high carbon	60° d = 3t
Bridge, building, car, and locomotive structural steel	Not over ¾ inch thick	180° d = 0
	¾ inch to 1¼ inch thick	180° d = 2t
	Over 1¼ inches thick	180° d = 2t
Rivet steel for bridges, buildings, boilers, ships, etc		180° d = 0

* (*d* = diameter of pin about which specimen of thickness *t* is bent.)

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* Yearbook, 1914.

STANDARD SPECIFICATIONS FOR COLD-BENDING TESTS OF VARIOUS STEELS.—*Continned.*

Character and use of Steel.				Cold Bend.
Eye-bar steel for bridges			Not over ¾ inch thick	180° d=t
			¾ inch to 1¼ inches thick	180° d=2t
			Over 1¼ inches thick	180° d=3t
Ship structural steel			Not over ¾ inch thick	180° d=t
			¾ inch to 1¼ inches thick:	180° d=1½t
			Over 1¼ inches thick	180° d=2t
Soft steel castings				120° d=2t
Medium steel castings				90° d=2t
Boiler and firebox steel			Not over 1 inch thick	180° d=0
			Over 1 inch thick	180° d=t
Billet steel concrete reinforcing bars	Plain bars	Structural Grade	Under ¾ inch thick	180° d=t
			¾ inch thick or over	180° d=t
		Intermediate Grade	Under ¾ inch thick	180° d=2t
			¾ inch thick or over	90° d=2t
		Hard grade	Under ¾ inch thick	180° d=3t
			¾ inch thick or over	90° d=3t
	Deformed bars	Structural grade	Under ¾ inch thick	180° d=t
			¾ inch thick or over	90° d=2t
		Intermediate grade	Under ¾ inch thick	180° d=3t
			¾ inch thick or over	90° d=3t
		Hard grade	Under ¾ inch thick	180° d=4t
			¾ inch thick or over	90° d=4t
Cold-twisted bars			Under ¾ inch thick	180° d=2t
			¾ inch thick or over	180° d=3t
Concrete reinforcing bars from rerolled rails		Plain bars	Under ¾ inch thick	180° d=3t
			¾ inch thick or over	90° d=3t
		Deformed bars	Under ¾ inch thick	180° d=4t
			¾ inch thick or over	90° d=4t

495. Behavior of Steel under Impact. Shock Resistance. The impact strength of steels is a matter of great interest to engineers, because the construction uses of the material in situations where some measure of impact is not encountered are very few. In view of this fact it is evident that the static load tests usually applied possess only a limited value if they fail to give any indication of the ability of the material to withstand the effect of suddenly applied loads. Unfortunately, the amount of published experimental data bearing on this question is rather meager, and much of that which is available loses its value (1) because of the employment of non-precise methods and equipment, (2) because of the failure of the experimenter to take account of some factors which have largely affected the character of the results obtained, or (3) because the method employed affords no basis of comparison with conditions of service or with other tests (like the static tension test for example), the relation of the results of which to the behavior of the material in service have been more or less accurately established.

Two general methods of subjecting steel and similar materials to impact have been extensively employed:

(1) Methods by which a specimen having a nick cut in the center of its length is supported horizontally on knife-edges and subjected to the blow of a falling hammer, and

(2) Methods of subjecting a specimen to tensile impact while gripped between the jaws of two cross-heads, the lower cross-head being suspended from the upper one by the specimen itself, and the tensile force applied by (*a*) allowing both cross-heads to fall freely, and suddenly arresting the motion of the upper one, the impact force being dependent upon the velocity and mass of the lower cross-head, or (*b*) by rigidly supporting the upper cross-head and allowing a falling hammer or tup to strike the lower one.

The transverse impact test has been extensively employed as an acceptance test of steel castings and forgings, and particularly so in Europe. The method of making the test and the type of machine employed has not been standardized, however, although the Copenhagen Congress of the International Association for Testing Materials in 1909 adopted a recommended method of performing the test which has not met with very general approval. It has been conclusively shown that the results of tests performed on specimens of different sizes are not comparable, even though the larger and smaller specimens are geometrically similar in form. The size, form, and sharpness of the nick or notch also affects results in a marked degree.

The lack of any generally accepted standard method of making the transverse impact test renders it impossible to quote data showing the relative transverse impact strength of various steels. Nevertheless, the experience of many experimental laboratories, and particularly that of many industrial establishments which have devised or adopted a test suited to their individual requirements, shows that tests not only can be made to be truly comparable, but that an indication of the suitability of a material for a special use is afforded which is not attainable by the ordinary tensile test.

A special form of the transverse impact test is the drop test of steel rails, which is the standard of the American Railway Engineering Association.* In this test a tup weighing 2000 pounds, and having a radius of 5 inches, is allowed to fall upon the central portion of a short section of a rail supported upon a span of 3 feet. The rail supports are secured

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* Proceedings, Vol. 15, 1914, p. 376, also Yearbook, 1914. Am. Soc. Test. Mat., p. 11.

to an anvil block weighing 20,000 pounds, the latter being carried by springs. The specified height of drop is from 16 to 18 feet, according to the weight of the rail under test, and the resulting amount of longitudinal distortion of the fiber and permanent deflection of the rail are not allowed to exceed specified amounts for each weight and form of rail. The requirements are also varied according to whether the rails are of Bessemer of open-hearth manufacture.

The tensile impact test is one which is somewhat difficult to so devise that the actual proportion of the energy of a blow which distorts the specimen may be accurately measured, the energy lost in distorting parts of the machine itself, or in causing vibration, being corrected for. This is especially true if the form of the machine is that of type *b* above mentioned.

Probably the most extensive series of tensile impact tests which has been made in recent years is that made at Purdue University under the direction of Prof. W. K. Hatt.* The machine used was of type *a* above mentioned, and especial care was taken to eliminate errors due to energy lost to the machine itself. A direct comparison is afforded by the Purdue tests between the tensile strength and ductility of various steels under static load and under impact load. On this account the following summary of the tests is introduced. Prof. Hatt adopts as a convenient basis of comparison of the behavior of a material under static and under impact loading, the work done in deforming a unit volume of the material to rupture. This quantity he terms the "unit

COMPARATIVE STATIC AND IMPACT STRENGTH OF STEELS

Material.	Ult. Tens. Strength. Lbs. Sq.in.	Elongation. Per Cent.		Rupture-Work. Ft.lbs. per Cu.in.		Ratio Static to Impact.	
		Static.	Impact.	Static.	Impact.	Elong.	Rup. Work.
Steel wire........	115,000	0.59	0.70	136	186	0.84	0.73
" "	71,000	14.10	13.60	742	765	1.04	0.97
" "	109,000	4.63	5.80	348	626	0.80	0.56
Annealed wire.....	83,000	9.30	7.00	566	544	1.33	1.04
Nickel steel.......	85,000	23.60	24.00	1,414	1,821	0.98	0.77
Soft steel..........	68,000	23.90	27.00	1,376	1,358	0.89	1.01
Boiler steel........	80,000	25.70	34.40	1,230	1,855	0.75	0.66
Soft steel casting..........	62,000	28.20	33.00	1,450	2,315	0.85	0.63
Locomotive tire steel........	140,000	13.10	14.30	976	2,918	0.92	0.33

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* Proc. Am. Soc. for Test. Matrls., Vol. 4, p. 282.

rupture work "* and proposes as a convenient method of determining it the operation of dividing the area of the stress-strain diagram by the volume of the specimen between gauge points.

It seems evident from the above data that the strength and ductility of most steels under impact loading are at least not inferior to those disclosed by the usual static tests. This conclusion is probably not applicable, however, to many alloy steels nor to many heat-treated carbon steels.

496. Behavior of Steels under Repeated and Alternating Stresses. Fatigue. That all metals may ultimately fail under oft-repeated stresses far below the ultimate strength shown by the conventional tensile or compressive test is a fact which has been well known for many decades. Such failures have often been observed in the case of axles of car-wheels, parts of moving machinery, etc., and the phenomenon has frequently been demonstrated in a scientific manner since the pioneer work begun by Wöhler in 1849 and reported in 1870. If the maximum stress approximates closely the ultimate strength, failure may, in the case of steels, be induced by perhaps less than a hundred repetitions; with a maximum stress not far from the elastic limit, from a few thousand to several hundred thousand repetitions may be required; and if the maximum stress does not greatly exceed one-half the elastic limit, rupture, if ever attained, will usually be produced only by millions of repetitions.

This phenomenon, common to all metals possessing any considerable elastic properties, was once ascribed to a general deterioration of the cohesion between crystalline constituents of the metal when subjected to many repetitions or reversals of comparatively low stresses. Owing probably to this idea of deterioration, the phenomenon came long ago to be known as the " fatigue " of metals, and the use of the term has persisted in spite of the fact that it is now known to be a process of gradual and progressive failure or fracture of the crystals themselves.

No detailed explanation of the fatigue failure of metals can be made in the present state of our knowledge of the subject, but a certain amount of light has been thrown upon the matter by facts established by the use of modern metallographic methods of study.†

Examination under the microscope of the behavior of the crystalline constituents of steels under stress, or the effect of high stresses upon

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* This term is more appropriately used than the term " resilience," which properly means the amount of energy which may be stored in a given material and recovered as mechanical work. The resilience of a body is equal to the work done in distorting it only if the elastic limit has not been exceeded.

† For a somewhat detailed consideration of the cause of the fatigue failure of metals see paper by Professors G. B. Upton and G. W. Lewis in " American Machinist," Vol. 37, p. 633.

their form and structural integrity, has shown that crystalline failure is usually a gradual process and not an instantaneous one. Whatever the character and manner of application of the external force acting on a piece of steel, the individual crystals are subjected either to tension or shear, and failure of the piece as a whole is a matter of the successive failure of individual crystals. Failure never occurs at crystalline boundaries.

The actual determining factors in fixing the average stress under which steel will rupture are (1) the stress to which the most stressed crystals are subjected, (2) the behavior of these crystals under load, and (3) the extent to which the failure of a limited number of crystals affects the structural integrity of the piece as a whole.

The stress to which the most stressed crystals are subjected under the action of a given external load is dependent chiefly upon the uniformity of distribution of stress between crystals, which in turn is dependent upon the homogeneity of the structure. (The pre-existence of internal stresses, originating during cooling, heat treatment, or mechanical working, is a factor which cannot be neglected but which cannot be quantitatively taken account of.)

The failure of ductile crystals under stresses exceeding their yield point is really a succession of shear slips on parallel planes of least strength. It is not altogether sudden, because after a slip occurs on one plane a new slip occurs on an adjacent plane. This is followed by a third slip, and thus the action proceeds, the ultimate plastic deformation of the crystal being made up of infinitesimal permanent slips on many slip planes. The plastic yielding of the softer crystals may radically change the stress conditions of the surrounding crystals which are still behaving elastically, and thus greatly affect the subsequent extent of variation of stress in the material.

The harder crystalline constituents of steels fail on planes of weakness in essentially the same manner as do the softer and more ductile crystals, but the fact that they possess a very high elastic limit causes failure to follow very soon after the proportionality of deformation to stress is lost. Their failure is in consequence considered sudden and they are called brittle.

The possibility of failure of crystals in tension instead of shear is dependent upon the orientation of the crystals with respect to the direction of stress. Moreover, since this is wholly a matter of chance, and the interactions between crystals are very complex, the possibility of tensile failure of crystals being an important factor in the ultimate breakdown of the crystalline aggregate is probably remote.

The extent to which the failure of a limited number of crystals affects the structural integrity of the piece as a whole is dependent chiefly upon the manner in which the stress is externally applied, being greatest when the distribution of stress is least uniform. Thus torsion loading is probably most hazardous, transverse loading slightly less so, and tensile loading most conducive to the attaining of a high average ultimate strength.

In the ordinary tension test, the load being gradually and perhaps continuously increased until rupture occurs, conditions are most favorable to high ultimate strength because of the opportunity afforded for adjustment of deformation under the action of the load. Especially after the yield point has been reached does this tendency toward equalization of stress become operative.

When, on the other hand, a load causing an average stress far below the ultimate strength is applied many times in succession, each occurrence of stress probably produces infinitesimal permanent shear slips which, if the load is not excessive, will at first be principally confined to the particular crystalline constituents whose limit of elastic behavior has been passed, owing to non-uniform distribution of stress or the preexistence of internal stresses. Further repetitions of stress not only produce more shear slips, but the cumulative effect of failures of individual crystals upon the uniformity of stress distribution probably means a gradual increase in the extent of the destructive action caused by each stress repetition. The number of repetitions of stress necessary to cause failure appears to be a function of the average intensity of stress repeatedly applied, but is also dependent upon the character, prevailing size, and structural arrangement of the crystalline constituents of the metal.

As the percentage of carbon is increased the proportion of relatively coarse crystals of ferrite decreases and the endurance of steels under repetitions of stress normally tends to increase until the carbon content approaches the eutectoid ratio. The relation of carbon content to the endurance of steels is very often masked, however, by the effect of other factors. Thus any heat treatment which tends to increase the size of crystals formed is very detrimental to endurance, and the presence of comparatively large amounts of phosphorus, manganese, etc., or the existence of internal stresses caused by the conditions of cooling, heat treatment, or mechanical working, may be factors whose influence outweighs that of carbon content.

Methods of subjecting steel to tests of its endurance have never been standardized, nor has anyone ever been able to show any close relation between the results of fatigue tests made in any manner with the results of the conventional tension test. This circumstance is not due to a lack of incentive, because manufacturers of automobile parts, engine castings and forgings, etc., would welcome an opportunity to standardize their products by endurance tests. Dozens of methods of making endurance tests have been proposed in the last forty years, and many fatigue-testing machines are on the market, yet none has received much attention by any parties other than its promoters.

Fatigue-testing machines, as a general rule, do not simply apply a stress of given character and intensity repeatedly, but the design of the machine in its relation to the test piece is such that stresses of opposite character are alternately applied, the usual arrangement causing the stress to vary continuously throughout a complete cycle from the chosen maximum tensile stress to a maximum compressive stress of equal intensity. Such a cycle of alternating stresses is often obtained by the rotation of a specimen which is at the same time subjected to bending by a force applied transversely in a constant direction. Another common type of machine which produces a similar cycle of stresses is one in which a specimen is securely clamped at one end and bent alternately forward and backward by the action of a reciprocating connecting rod actuated by a revolving crank or eccentric. Experience has shown that repetition of alternating stresses in a complete cycle is a more severe test of a material than is the repetition of a stress of the same maximum intensity without reversal.

The relative endurance of a series of carbon steels covering a considerable range of carbon content and tensile properties is exhibited by Fig. 273. The tests upon which these curves are based were made at the Watertown Arsenal on a machine which applied transverse loading at the center of the span of rapidly rotating shafts.* Logarithmic coordinates have been used in plotting the curves as a matter of convenience, though it does not appear that the relation between the maximum intensity of stress and the number of cycles of stress required to produce failure is an exponential one, since, were that the case, the curves would be straight lines.

The lack of smoothness of the curves appears indicative of a lack of precision in the testing methods employed, for the steel bars of a given carbon content were all taken from the same hot-rolled shaft, and exhibited practically no variation in properties in tensile tests. Because of this apparent lack of accuracy in the test results, and the further fact that each curve

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* "Tests of Metals," 1903-1909. Fig. 273 summarizes the results of all tests of "Gautier" steels made between the years 1902-09. These tests have been selected from the series of over 400 tests made at Watertown Arsenal between 1889 and 1909 because they comprise the most comprehensive series of tests of one class of steels available.

represents the result of only one test at each stress intensity, the drawing of any detailed conclusions from these tests is unjustified. Attention may be called, however, to certain general indications which are in accord with the teachings of common practical experience:

(*a*) For all classes of carbon steels the endurance under alternating stress increases very rapidly as the maximum stress intensity decreases.

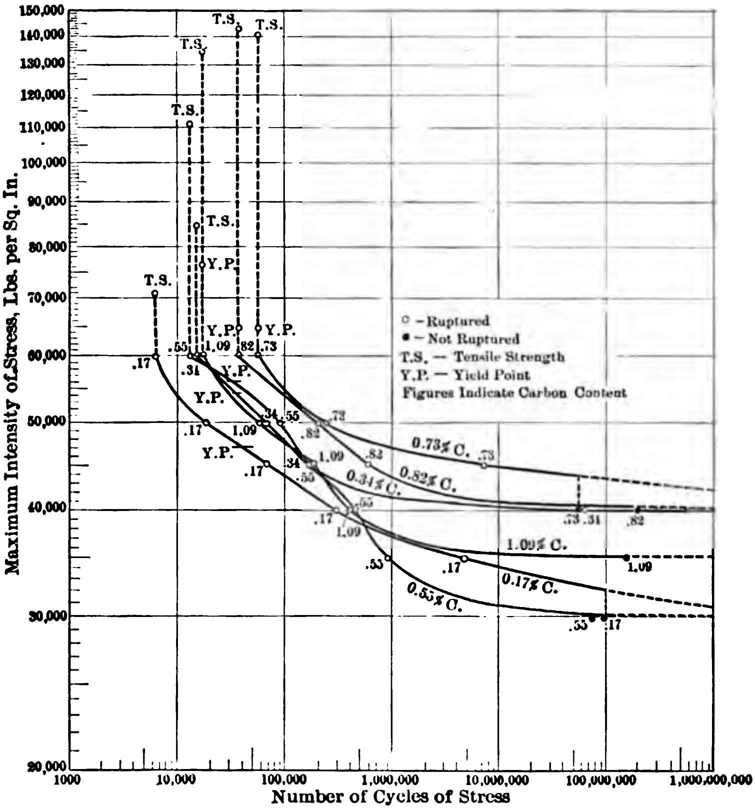

FIG. 273.—Endurnace of Steels under Alternating Stresses. (Watertown Arsenal Tests, 1903–1909.)

(*b*) The endurance of carbon steels of fairly high carbon content usually excels that of either low, medium, or very high (hyper-eutectoid) carbon content.

(*c*) Fatigue failure of any class of carbon steel when the maximum intensity of stress does not exceed about 30,000 pounds per square inch will rarely be encountered, and for steels of fairly high carbon content the limit appears to be still higher.

Adequate trustworthy data are not available to permit study of the effect of various heat treatments upon the endurance of steels. Experience seems to show, however, that moderate hardening or hardening followed by careful tempering, is beneficial, but that extreme hardening, or annealing at very high temperatures, is detrimental.

497. The Magnetic Properties of Steel. The magnetic properties of iron and steel are of great practical importance for two reasons:

(1) Enormous quantities of iron and steel are used in the construction of electrical machinery, motors, generators, transformers, etc., where the magnetic properties of the material used are of supreme importance; and

(2) Magnetic properties and mechanical properties of irons and steels are dependent upon the same factors, i.e., composition, heat treatment, mechanical working, etc. The mechanical properties can therefore, at least in a measure, be foretold by the results of magnetic testing.

The following explanations of terms and units used in magnetic measurements are here inserted to clarify the succeeding discussion of magnetic properties:

Magnetic lines of force are considered to permeate a magnetic field and indicate by their form the direction of magnetic force at any point. By their closeness to each other they also show the magnitude of the force.

Magnetic density or intensity are terms employed to express magnitude of induced magnetism. The C. G. S. unit of intensity is the *Gauss*, which is one magnetic line of force per square centimeter. Magnetic intensity measured in gausses is conventionally represented by the symbol $\mathfrak{B}$.

Magnetizing Force. When any material is magnetized by the action of an electric current flowing in a coil, the intensity of the magnetism produced is dependent upon the strength of the magnetizing force. The total magnetizing force is the product of the number of turns and the current flowing in them. The C. G. S. unit of magnetizing force is the *Gilbert*, which is the magnetizing force required to produce unit magnetic intensity in a circuit of air 1 centimeter long and 1 centimeter in cross-section. Magnetizing force measured in gilberts is conventionally represented by the symbol $\mathfrak{H}$. (The term *gauss* is sometimes used to express both the intensity of induced magnetism and that of the magnetizing force.)

Permeability. The intensity of magnetism produced in iron or steel by an increasing magnetizing force does not increase in direct proportion to the magnetizing force, but, as the latter increases, the ratio of the intensity to the magnetizing force producing it decreases. The value of this ratio, which varies not only with the intensity or with the magnetizing force, but also with the chemical character and past history of the iron or steel magnetized, is called "permeability." Curves representing the relation between intensity and magnetizing force are called "induction curves," or "$\mathfrak{B}$ and $\mathfrak{H}$ curves." The slope of the induction curve at any point is the permeability. The conventional symbol for permeability is μ. Typical induction curves for a number of irons and steels are presented in Fig. 274.

Hysteresis. The magnetization of iron or steel involves a molecular change which cannot be accomplished without encountering a certain amount of resistance which is overcome by the expenditure of energy.

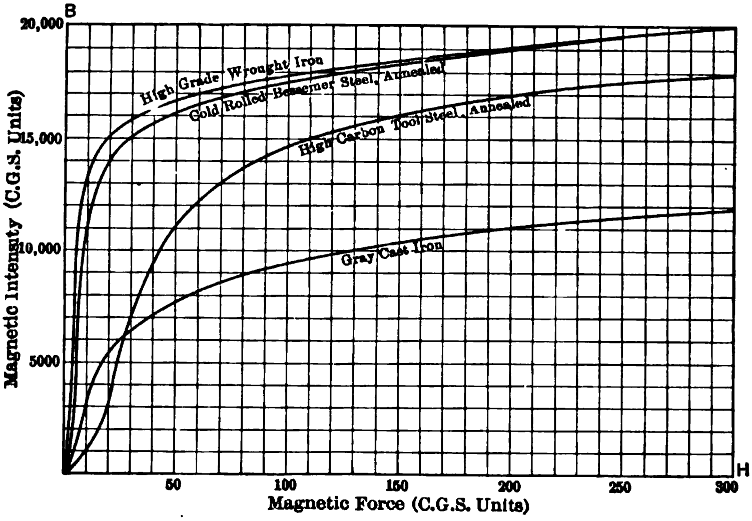

FIG. 274.—Typical Induction or *B-H* Curves.

The change of intensity of magnetism induced therefore lags behind a change of magnetizing force, and if the magnetizing force is one which is periodically varying harmonically between a maximum positive value and a maximum negative value, as is the case when the magnetizing coil is excited by an alternating current, the loss of energy due to the constant necessity of overcoming molecular resistance to change of state becomes a very considerable portion of the total energy expended. This phenomenon of the lag of magnetization behind the magnetizing force is called "hysteresis," and the energy loss occasioned by it is called "hysteresis loss."

Consider, for instance, the magnetizing of the steel represented by the curves of Fig. 275, the magnetizing force being one produced in an exciting coil by an alternating current. As the magnetizing force increases in a positive direction, the corresponding intensity of magnetism in the steel is represented by the dotted induction curve *OA*. At *A* the direction of the magnetizing force reverses and decreases to zero. The magnetism induced ceases to increase and immediately begins to decrease, but, owing to hysteresis, does not at first decrease in positive value at the rate corresponding to the magnetizing force which characterized its first increase. As a result when the magnetizing force has become zero the steel still possesses a positive magnetism, the intensity of which is indicated by *OE*. As the magnetizing force continues to decrease positively (increasing negatively), the induced magnetism decreases and becomes of zero intensity when the magnetizing force has the negative value *B*. Thereafter the magnetism becomes negative and increases negatively until the magnetizing force again reverses direction at *C*. After the alternating current has passed through a few cycles the cyclic variation of the magnetism induced comes to be represented by the closed loop *ABCD*, whose area represents the hysteresis loss. If the maximum magnetizing force had been that represented by *A'* and *C'*, the hysteresis loss would be represented by the loop *A'B'C'D'*. The locus of the points *A* and *C* is evidently the induction curve.

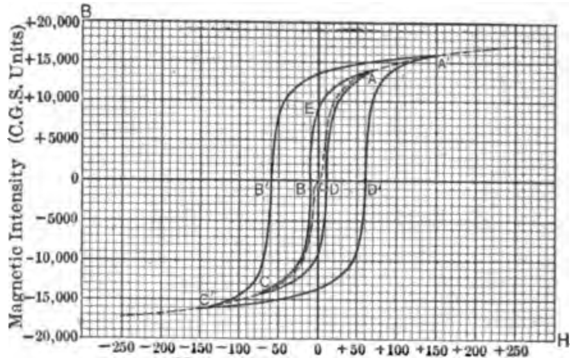

FIG. 275.—Hysteresis Curves for Steel.

The loss due to hysteresis is for a given iron or steel approximately directly proportional to the rate of change of magnetism, or, as commonly stated, the frequency. It also increases approximately proportional to the 1.6 power of the maximum magnetic intensity which is attained during a cycle (Steinmetz's law), and since the latter is dependent upon the chemical character and past history of the iron or steel the hysteresis loss varies with different steels.

Eddy Current Loss. Besides the hysteresis loss, with cyclic variation of magnetizing force, a certain amount of energy is wasted in "eddy currents." These are currents of electricity produced in the iron or steel because of the varying magnetic fields. The eddy current loss in the cores of transformers, generators, motors, etc., is greatly reduced by building them up of thin sheets of metal, insulated from each other by a coating of varnish or paper, or by the natural scale on the surfaces. The sheets are so placed as to lie in a direction normal to the direction of flow, and the circuits of the eddy currents are thus broken up.

Core Loss. The hysteresis loss and the eddy current loss cannot easily be separately determined. The total loss of energy due to both is therefore determined, and called the " core loss " or "iron loss." It is expressed by " the total power in watts consumed in each kilogram of material at a temperature of 25° C., when subjected to a harmonically varying induction having a maximum of 10,000 gausses and a frequency of 60 cycles per second . . . It is represented by the symbol $W_{10/60}$." *

The magnetic properties of iron and steel which are of the greatest practical importance from the standpoint of the manufacture of electrical machinery are (1) the permeability, and (2) the core loss. Methods of testing these two properties have been standardized by the American Society for Testing Materials,† and by the U. S. Bureau of Standards.‡ Magnetic tests are of fundamental importance to the manufacturer, because he thereby insures the uniformity of magnetic qualities in his materials, which is essential if the performance of electric machines is to be predetermined. Otherwise the manufacturing economy attained by the use of standard dimensions and windings for many machines of the same rating would not be possible.

High permeability is desirable in an iron or steel used in the construction of electrical machinery not simply because weight and bulkiness of machines is lessened, but particularly because the strength of the magnetizing force required is thereby reduced, which means that less copper in the exciting coils, and less current, is required to produce a given intensity of magnetic induction.

By the substitution of cast steel for cast iron for the yokes, frames, and other parts of dynamos and motors which are not made of laminated sheet metal or copper wire, a considerable economy is effected because of the much greater permeability of cast steel, which is in fact about equal to that of good wrought iron except with low values of the magnetizing force. (In spite of the higher efficiency which might be obtained, few electrical machines are built in this country with cast-steel frames, etc., except for export. Pressed steel is considerably used, however.)

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* " Standard Specifications for Magnetic Tests of Iron and Steel." Yearbook, Am. Soc. Test. Matrls., 1914.

† " Standard Specifications for Magnetic Tests of Iron and Steel." Am. Soc. Test. Matrls., Yearbook, 1914.

‡ Technical Paper No. 117.

For the laminated sheet metal used for the cores of armatures, the pole pieces of dynamos and motors, cores of transformers, etc., a high-permeability iron or low-carbon steel has until recent years always been used. Consideration of the possibility of reducing the core loss, by the use of a material whose hysteresis loss and eddy current loss are less than those of even a very pure iron, has led to the development of certain alloy steels possessing an extremely low carbon content but containing 2 to 4 per cent of silicon. This silicon steel, or silicon iron, as it may perhaps be more properly called, exhibits an hysteresis loss very much below that of an ordinary iron, and, in addition, possesses a somewhat higher degree of resistivity to the passage of current, and consequently reduces in a measure the eddy current loss.

Relation between Magnetic Properties and Chemical Composition

The following conclusions have been arrived at by de Nolly and Veyret as the result of an investigation of the hysteresis and eddy current losses of dynamo sheet metals of varying chemical composition.*

Carbon. "The carbon percentage should be as low as possible and always remain below 0.1 per cent." A 0.15-per-cent-carbon steel is greatly inferior to one containing 0.10 per cent carbon.

Silicon. "The presence of silicon diminishes the hysteresis losses considerably. The coefficient η changes from 0.0016 for an iron free of silicon to 0.0009 for a metal containing 3.5 per cent silicon." Silicon also increases the resistivity of the steel and therefore reduces eddy current losses by about 25 per cent. In a very weak field (below 5 to 10 gausses) silicon increases permeability, but with stronger magnetizing force the effect is reversed and permeability is diminished very much.

Manganese. Manganese appears to be detrimental to magnetic properties if present in amounts exceeding about 0.3 per cent. The data secured bearing upon the effect of manganese are not very conclusive.

Sulphur and Phosphorus. Both sulphur and phosphorus were found to be elements whose presence in amounts exceeding about 0.3 per cent (for both combined) constitute a distinct injury to magnetic properties. A steel containing 0.15 per cent sulphur gave very poor results although it was a 0.1-per-cent-carbon steel.

Relation between Magnetic Properties and Temperature

Investigation of the changes in magnetic properties of steels as the temperature of the specimen under test is raised or lowered has been

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* Proc. Sixth Congress, International Assoc. for Test. Matrls., New York, 1912, paper IX_5.

made in only a few instances, and little detailed information is available. The most extensive study yet made is probably that reported by the Chemical Laboratory of Messrs. Schneider's Works at Creusot,* and the following remarks are based wholly upon this report.

The method of study followed consisted in subjecting steel specimens of various forms to uniformly increasing and decreasing temperatures in an electric furnace, and simultaneously exposing them to a chosen constant magnetizing force. The temperature indications of a thermocouple mounted in the specimen, and the corresponding intensity of induced magnetism were continuously recorded autographically on a curve, the ordinates to which are values of $\mathfrak{B}$, and the abscissae temperatures in degrees.

One of the facts most emphatically shown by the test results was that the form of the curve obtained varies considerably for specimens of different forms. The maximum strength of magnetizing force employed also had a marked effect upon the character of the temperature-inductance curve. Because of these considerations the author has selected from the test results only those obtained with the form of test specimen which was least subject to disturbing influences (such as the demagnetization caused by the poles), and has further limited his selection to the results obtained with the maximum strength of field which seemed to bring out most clearly the characteristic differences of behavior of the various steels tested.

The specimens used in the series of tests selected were 200 millimeters long, 3 millimeters in diameter, and comprised a series of six steels varying in carbon content from 0.06 per cent to 1.20 per cent. The maximum strength of field employed was 20 gausses and the frequency 45 cycles per second. The test results are indicated by the curves of Fig. 276. The cooling curves are given negative ordinates in order to avoid confusion of the diagram.

It will be noted at once that the most pronounced change of magnetic properties occurs when the critical range of temperatures is reached, at which point an almost total loss of magnetism takes place. The critical points A_1, A_2, and A_3 may be located with a fair degree of accuracy on the curves.

Aside from the great change in magnetism which takes place in passing the critical range of temperatures, other changes of lesser magnitude occur at lower temperatures. In the case of the three steels of lowest carbon content there is a progressive increase in induction up to a temperature of about 200 or 250° C. The explanation of this phenomenon

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* Proc. Sixth Congress, International Assoc. for Test. Matrls., New York, 1912, paper IX_1.

is not definitely understood, but seems to be attributable partly to the magnetic viscosity of mild steels at these temperatures, which may restrain magnetism.

All of the medium- and high-carbon steels exhibit a certain falling off in magnetism in passing through the range just below 200° C., the loss becoming accentuated as the percentage of carbon increases. This behavior appears to be due to the fact that iron carbide loses its magnetism to a very large degree at a temperature in the neighborhood of 200° C. The phenomenon is naturally most marked therefore when the total carbon content and therefore the carbide content is greatest.

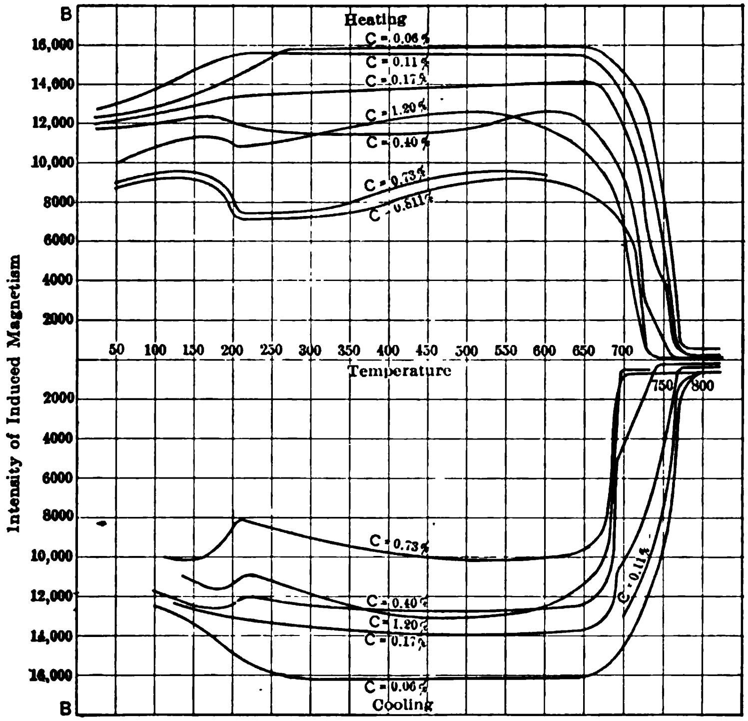


Fig. 276.—Relation of Magnetic Induction to Temperature. (Messrs. Schneiders' Works, Creusot.)

The fact that the magnetic properties of the 1.2-per-cent-carbon steel appear to excel those of the 0.73-per-cent and the 0.911-per-cent-carbon steels, appears to be due to the fact that the micro-structure of the latter two was largely that of lamellar pearlite, the series of inclusions of carbide in which might be considered to oppose the passage of magnetic lines of force much more effectively than when the carbide occurs in small globules disseminated throughout the ferrite, as was found to be the case in the 1.2-per-cent-carbon steel.

Relation between Magnetic Properties and Mechanical and Thermal Treatment

The effect of various mechanical treatments on a very low-carbon, medium-silicon, dynamo sheet steel is indicated by the curves of Fig. 277, which have been selected from the series of tests made by de Nolly and Veyret and cited above.

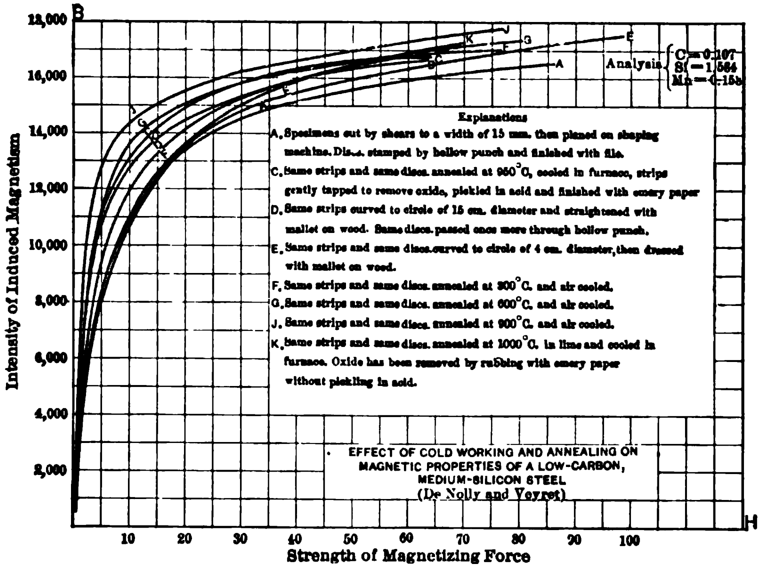


FIG. 277.

It appears that the cold working involved in stamping the specimens with a hollow punch is injurious to their magnetic properties, as is shown by a comparison of curves *A* and *C*, the latter representing specimen *A* after annealing. Curves *D* and *E* show that cold working by slight bending, followed by straightening with the mallet on wood, is injurious in proportion to the amount of distortion or cold working. Annealing at 300° C. removes the injurious effect of cold working in a measure (curve *F*), but is less effective than annealing at higher temperatures, as shown by curves *G* and *J*. The maximum benefit seems to be derived by annealing at 900° C., for when the annealing temperature is raised to 1000° (curve *K*) a less magnetic steel is derived.

The effect of various hardening and annealing treatments upon the magnetic properties of a 1.0-per-cent-carbon spring steel is shown by the curves of Fig. 278, which has been abstracted from a preliminary report by Mr. C. W. Burrows upon the study of magnetic properties of irons and steels made at the U. S. Bureau of Standards.* It will be noticed that for this high-carbon steel the magnetic properties are slightly improved by annealing the steel as received, scarcely affected by quenching below the critical temperature, very considerably impaired by quenching in oil, and enormously impaired by water quenching.

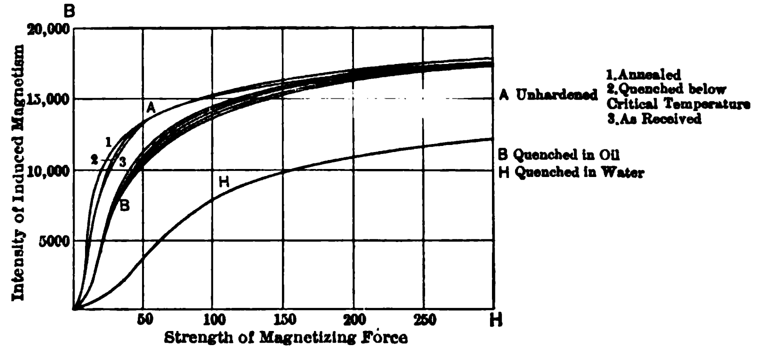
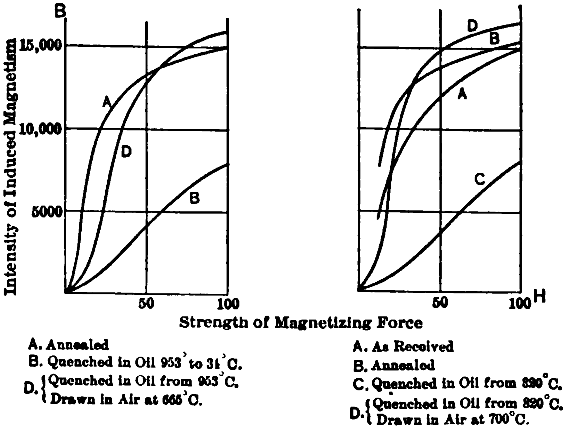


Fig. 278.—Normal Induction Curves for a 1 per cent Carbon Spring Steel after Various Heat Treatments. (Burrows.)



(*a*) (*b*)

Fig. 279.—Effect of Special Heat Treatment on Magnetic Properties of Steels. (Burrows.)

(*a*) 1.0 per cent Carbon Steel. (*b*) 0.8 per cent Carbon (1.0 per cent Manganese) Steel.

The effect of quenching, and quenching followed by tempering, is shown again by the curves of Fig. 279. It should be particularly noted that these spring steels exhibit peculiar magnetic properties when tempering follows hardening. At low inductions the magnetic properties are rather

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* Proc. Am. Soc. Test. Matrls., Vol. 13, p. 570.

low, but at inductions exceeding about 13,000 gausses they excel the annealed material.

Relation of Magnetic to Mechanical Properties

The relation of magnetic properties of steels to their mechanical properties is under investigation at the U. S. Bureau of Standards, but the only information yet available is that relating to the study of magnetic criteria of a 1.0-per-cent-carbon steel above alluded to.

Fig. 280 exhibits the relation found between intensity of magnetic induction under a magnetizing force of 50 gausses, and the elastic limit in bending of the steel. Steels containing 1.0 per cent carbon were used in all tests, the elastic limit being varied by subjecting the individual specimens to different hardening and tempering treatments. The curve shows that the highest induction corresponds to the lowest mechanical strength (that of the annealed steel), and the decrease in induction follows very closely with increase in quenching temperature, other things being equal. The mechanical strength increases up to a maximum value with decrease in induction, and thereupon decreases as the induction continues to decrease.

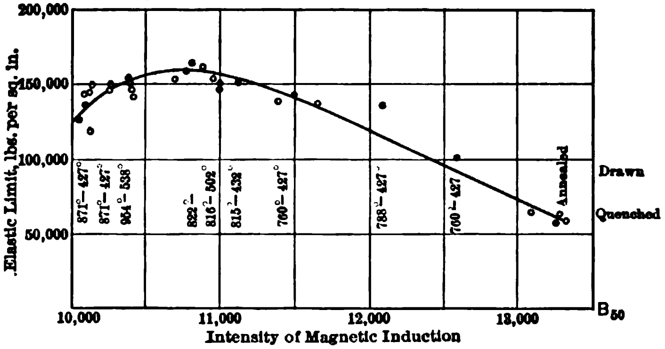

FIG. 280.—Relation between Maximum Fiber Stress at Elastic Limit and Magnetic Induction under a Magnetizing Force of 50 Gausses for a 1.0 per cent Carbon Steel. (Burrows.)

Fig. 281 exhibits the relation found between the induction secured at 50 gausses and the angle of cold bend at which 1.0-per-cent-carbon steels, variously heat treated, will rupture. The curve shows an increase of the angle of bend as the induction decreases; a maximum angle is passed, and further decreases in induction mean a decrease in the angle of bend. The maximum angle of bend occurs at a higher induction than does the maximum fiber stress in bending. This would seem to indicate that the most serviceable steel would be one whose induction is a compromise between that corresponding to the maximum fiber stress and

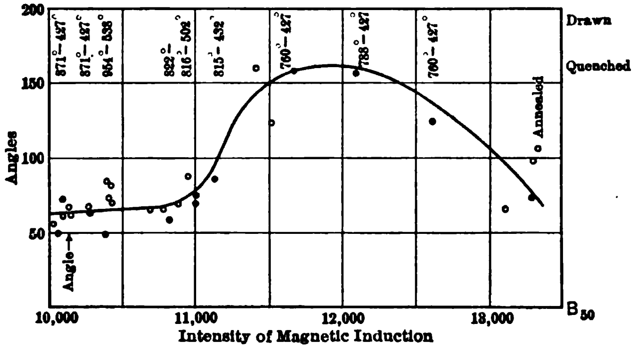

FIG. 281.—Relation between Angle of Cold Bend and Magnetic Induction under Magnetizing Force of 50 Gausses for a 1.0 per cent Carbon Steel. (Burrows.)

that corresponding to the maximum angle of bend. If the induction were lower, the steel might be expected to lack toughness; if higher, the mechanical strength will be low.

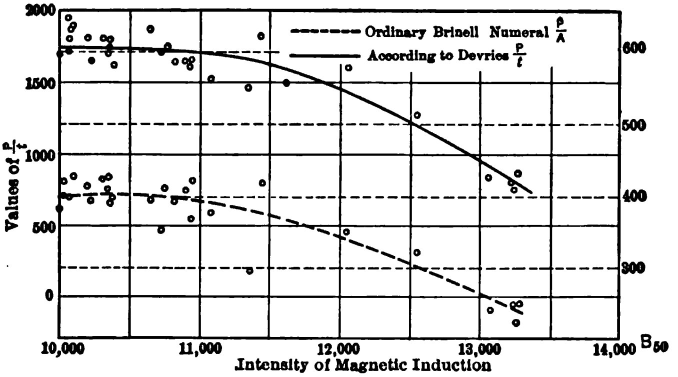

FIG. 282.—Relation between Brinnell Hardess and Magnetic Induction under a Magnetizing Force of 50 Gausses for a 1.0 per cent Carbon Steel. (Burrows.)

A comparison between magnetic induction and the hardness, as shown by the Brinell test, is afforded by Fig. 282. Both the hardness expressed by the ordinary Brinell number (based upon the area of spherical indentation) and the Devies hardness numeral (based upon the depth of indentation) are compared with induction at 50 gausses on this diagram. The curves show a general increase in hardness accompanying a decrease in magnetic induction.

498. The Corrosion of Iron and Steel. The importance of the durability of iron and steel when exposed to the various conditions of service has long been recognized, as is shown by the fact that the technical journals and the transactions of the Societies devoted to engineering or its allied sciences have long teemed with contributions and discussions bearing upon the general problem of the corrosion of iron and steel. Unfortunately, much of the literature of the subject is of a distinctly controversial nature, owing to the fact that students of the subject are far from being agreed upon what the true explanation of the phenomenon is. Furthermore, various experimental studies of the relative corrodibility of different materials have, because of their contradictory results, led to opposing conclusions concerning the effect of various factors such as relative composition, constitution, structure, etc.

The end product of the process of corrosion, i.e., rust, is well known to be simply ferric oxide plus a variable amount of combined water, and all authorities are agreed that corrosion of iron is possible only when both oxygen and water are present. Iron will not rust in perfectly dry air; on the other hand, it cannot rust in water which is entirely free from oxygen. It is further well known that certain conditions encountered in practice, such as a very humid atmosphere, exposure to acid fumes, acid-bearing air or waters, or water containing dissolved salts, tend to accelerate corrosion. At about this point universal agreement between authorities ceases to exist, however, and it becomes necessary, in proceeding to consider further the vexatious problem of corrosion, to recognize the existence of conflicting theories, a number of which are strenuously supported by competent authorities. In the following very brief discussion of these theories the author has been guided principally by the works of Dr. A. S. Cushman, Director of the Bureau of Industrial Research in Washington, D. C., who is probably the foremost American authority on the subject.*

Of the many theories advanced to account for corrosion three have gained widest recognition. These are, in the order of their present importance: (1) the electrolytic theory, (2) the hydrogen peroxide theory, and (3) the carbonic acid theory. The electrolytic theory, which is now accepted by the greater number of authorities, is much more complex than are the two other theories above mentioned, and on this account the latter two will be briefly explained first.

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* See particularly the work of Cushman and Gardner, "The Corrosion and Preservation of Iron and Steel," 1910, and the various contributions of Dr. Cushman in the Proceedings of the Am. Soc. Test. Matrls., 1906–1913.

The carbonic acid theory asserts that the hydroxylation of iron cannot take place without the interaction of carbonic or some other acid. The acid changes the metal to a ferrous salt with evolution of hydrogen:

$$2Fe+2H_2CO_3=2FeCO_3+2H_2.$$

The water and oxygen now react with the ferrous salt, forming ferric hydroxide and setting free all the acid originally used:

$$2FeCO_3+5H_2O+O=2Fe(OH)_3+2H_2CO_3.$$

A small amount of acid is sufficient to rust a large amount of iron, because it is set free again immediately after having combined with the iron to form the ferrous salt.

This explanation of corrosion is entirely plausible, and the fact is well known that acids do often act a part in promoting the corrosion of iron, but the theory has been discredited by a number of investigators, including Cushman, who have shown, by methods so carefully planned and executed as to leave scarcely room for questioning the accuracy of their results, that iron will corrode in water containing oxygen, but not a trace of carbonic acid. Corrosion will even take place in dilute alkaline solutions in spite of the fact that the alkali would neutralize any acid present.

The hydrogen peroxide theory explains corrosion by stating that water and oxygen react with iron to form ferrous oxide and hydrogen peroxide, whereupon one-half of the peroxide combines with the ferrous oxide to form hydrated ferric oxide, the excess of peroxide remaining to form a further amount of rust. Thus:

$$2Fe+2O_2+2H_2O=2FeO+2H_2O_2=Fe_2O_3,H_2O+H_2O_2.$$

This theory has failed to gain any substantial corroboration as the result of experimental investigation, and is largely discredited by the fact that the most delicate tests have always failed to detect even the transitory presence of the peroxide during the ordinary process of rusting.

The electrolytic theory of corrosion cannot be explained without a preliminary statement of certain of the fundamental principles of the theory of solutions, electrolytic dissociation and electrolysis.

Water is the one universal solvent for all forms of matter, and the common terms "soluble" and "insoluble" express simply relative solubility. A soluble substance readily passes into solution, but an insoluble one does so only with great reluctance. When a substance of the first class passes into solution "its molecules or atoms (depending upon whether the substance in question is a compound or simple element) tend to distribute themselves equispacially among the molecules of the solvent. The driving force which produced this tendency . . . is known as *solution tension* or *solution pressure* " and is not a constant except for a given substance in a given physical and thermal state.

As the number of particles in solution increases, there arises a back pressure, acting against the solution tension. This is what is known as *osmotic pressure.* " It is at once apparent that for any given substance at a given temperature, its maximum solubility would be reached just as soon as the solution pressure and the osmotic pressure were equal." External causes may operate to reduce the osmotic pressure, however, and the extent of the solvent action be thereby increased.

In analyzing certain studies of osmosis van 't Hoff * made the momentous discovery that with a certain class of substances, chiefly of organic nature, the osmotic pressure of a solution of the substance is exactly equal to the gas pressure of a gas having the same number of molecules in a given volume. This meant that the osmotic pressure of these solutions follows the law of Boyle for gases, which states that the pressure of a gas varies directly with its concentration.

Van 't Hoff further pointed out that another class of substances including the acids, bases, and salts of inorganic chemistry, did not obey the gas law, but in many cases showed osmotic pressure far out of proportion to the concentration of the solution. This observation led Arrhenius to question whether inorganic compounds entering solution might not simply dissociate molecularly, but actually break down into ultimate constituent particles or atoms which he called *ions.* This was the beginning of the modern theory of electrolytic dissociation.

The theory of electrolytic dissociation asserts that when any compound of the class of the acids, bases, and salts of inorganic chemistry is dissolved in water to form a dilute solution, its molecules break down into atoms or groups of atoms called *ions.* The ions originating from the dissociation of a molecule all carry charges of static electricity. The charge of some ions is positive, and of others negative, but the positively charged ions of a molecule are always opposed by ions whose total negative charge is exactly equal in amount. The positively charged ion is called a *cation*, and the negatively charged one an *anion.* Thus hydrochloric acid (HCl) dissociates into a cation, hydrogen ($\overset{+}{H}$), and an anion, chlorine ($\overline{Cl}$). Certain ions carry two or three times the ordinary charge, and are then termed *bivalent* or *trivalent* ions, while the ordinary ion is *univalent.* Thus calcic hydroxide ($Ca(OH)_2$) forms the bivalent cation ($\overset{++}{Ca}$) and also a bivalent anion ($\overset{-\,-}{OH}$). Hydrogen is

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* Zeit. Phys. Chem. I., 481 (1887).

the cation of all acids, and the hydroxyl (OH) is the anion of all bases. No compound shows acid properties unless the characteristic hydrogen ion is present, nor can a compound be basic without the characteristic hydroxyl ion. The anion of acids, the cation of bases, and both the anion and the cation of salts vary with different acids, bases or salts.

A second method of formation of ions which characterizes many processes of electrolysis, is the taking of its charge from an ion by an atom, the ion thereby becoming an atom while the original atom becomes an ion. Thus copper may be precipitated from a solution of copper salt by the action of zinc atoms robbing the copper ions of their positive charge. Similarly a metal placed in an acid solution will form positively charged ions by taking the positive charge of the hydrogen ions.

The third method of ion formation consists of the simultaneous formation of ions of opposite character by atoms of two different substances. Thus, when gold is placed in a chlorine solution the atoms of gold becomes positively charged, each gold atom becoming a cation, and at the same time a sufficient number of chlorine atoms assume a negative charge, becoming anions, so that a perfect balance between positive and negative charges is maintained.

The fourth and last known method of formation of ions depends upon the fact that an atom of a substance introduced into a solution of another substance may be able to assume a charge and become an ion by causing the valence of an oppositely charged ion in the solution to be increased, thus maintaining equilibrium. For instance chlorine added to a ferrous chlorine solution forms an anion and at the same time causes the ferrous (bivalent) ion to change to the ferric (trivalent) ion. This last example is illustrative of the true nature of the process known in chemistry as oxidation, and the reverse phenomenon is illustrative of the process of reduction. There is absolutely no conflict between the use of the term " valence " in the present instance as a measure of the electrical state of the ion, and the ordinary use of the term in chemistry meaning the combining power of a given atom for other atoms.

Electrolysis is that phenomenon which takes place whenever a current of electricity passes through a solution which is capable of conducting the current. Only those substances which in solution form ions are capable of conducting current, and they do so not as a metallic wire does, but by a migration of the ions toward the electrodes. Substances which form solutions which will carry current are known as *electrolytes.* If, for instance, a current is passed through a solution of hydrochloric acid the positive hydrogen ions proceed to the negative pole of the external circuit, give up their charge, and go out of the solution as atoms of gaseous hydrogen. At the same time chlorine ions are proceeding to the positive pole where an equal negative charge is given up and particles of chlorine are precipitated out.

It is not necessary that there be an external source of electric current in order that electrolysis may take place, as is evidenced by the familiar voltaic cell or element. When two more or less dissimilar metals are placed in an electrolytic solution and connected by an external conductor, current will pass through the external circuit and electrolysis will take place in the solution. Whichever one of the metallic terminals or electrodes is most strongly electro-positive will discharge positive ions into the solution which, together with the positive ions of the solution, proceed to the other terminal, give up their charge, and go out of the solution. At the same time the negatively charged ions of the solution migrate to the more strongly electro-positive terminal and give up their charge and go out of the solution.

Consider, for example, the voltaic cell, the electrodes of which are plates of zinc and copper, and the electrolyte sulphuric acid. Zinc is more strongly electro-positive than copper, and therefore discharges zinc ions, which join the hydrogen ions of the hydrochloric acid solution, and proceed to the copper electrode, give up their positive charge, and leave the solution as hydrogen gas and precipitated zinc. At the same time the ions of SO_4 in the electrolyte migrate to the zinc electrode, give up their negative charges and precipitate out. The copper thus becomes the positive electrode and the zinc the negative electrode, and the amount of current which passes through the external circuit from the copper to the zinc is equal to the total amount of the electrical charges carried by the ions of the electrolyte. The zinc gradually wastes away and the electrolyte becomes impoverished in acid, but the copper remains unaffected.

So great a dissimilarity between the electrolyte as exists in the case of zinc and copper just cited is not at all necessary to make electrolytic action possible in some degree. Cushman and Gardner illustrate the point by stating that "even two steel needles from the same package are sufficiently dissimilar to show a slight difference of potential when coupled in such a way, and one will be protected while the other suffers accelerated corrosion." This fact is one of supreme importance in connection with the electrolytic theory of corrosion, as will be shown in the discussion which follows.

The Electrolytic Theory of Corrosion Explained. Cushman and Gardner * have concisely stated the electrolytic theory of corrosion in the following terms: "Iron has a certain solution tension, even when the iron is chemically pure and the solvent pure water. The solution

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* Loc. cit., p. 44.

tension is modified by impurities or additional substances contained in the metal and in the solvent. The effect of the slightest segregation in the metal will throw the surface out of equilibrium, and the solution tension will be greater at some points than at others. The points or nodes of maximum solution pressure will be electro-positive to those of minimum pressure, and a current will flow, provided the surface points are in contact, through a conducting film. If the film is water, or in any way moist, the higher its conductivity the faster the iron will pass into solution in the electro-positive areas, and the faster the corrosion proceeds. Positive hydrogen ions migrate to the negative areas, negative hydroxyls to the positives. . . .

"If the concentration of the hydrogen ions is sufficiently high, which . . . is only the same as saying, if the solution is sufficiently acid, the hydrogen ions will exchange their electrostatic charges with the iron atoms sweeping into solution, and gaseous hydrogen is seen escaping from the system. This takes place whenever iron is dissolved in an acid. If, however, as is usual in ordinary rusting, the acidity is not high enough to produce this result, the hydrogen ions will polarize to a great extent around the positive nodes without accomplishing a complete exchange, and the so-called electrical double layer of Helmholtz will be formed. This polarization effect resists and slows down action. Nevertheless, although it cannot be seen, some exchange takes place and iron slowly pushes through, . . . (and) for every exchange of static charge between iron and hydrogen at the positive node, a corresponding negative hydroxyl ion appears at the negative node. . . . In other words, as fast as the iron sweeps into solution the concentration of ferrous hydroxide grows, but the ferrous reaction appears in one place and the hydroxyl in another. It is now that the oxygen of the atmosphere dissolved in the solution takes up its work, the ferrous ions are oxidized to the insoluble ferric condition, which results in the precipitation of rust. . . ."

From the above discussion of corrosion it must be apparent (if the electrolytic theory is accepted) that the relative corrodibility of irons and steels under given conditions of exposure to air and moisture, with or without the accelerating effect of acid, will be in a large degree a function of their relative chemical purity and structural homogeneity. It is very difficult to demonstrate these propositions experimentally, however, because of the complexity of the problem and the limitations imposed upon the investigator in his efforts to eliminate all factors except the one under special study.

One of the favorite methods of investigating the relative corrodibility of various irons and steels has been by acceleration tests, the media employed being an acid solution which, compared with the ordinary conditions of rust formation, is a very potent electrolyte. It may well be doubted whether the comparative results obtained under such circumstances can be relied upon as a certain indication of the behavior of the materials under the conditions of natural rust formation. Nevertheless it is probable that accelerated tests carefully conducted do indicate certain general tendencies which have an important bearing upon the practical problem of how irons and steels may best be made and handled to produce the least corrosive material.

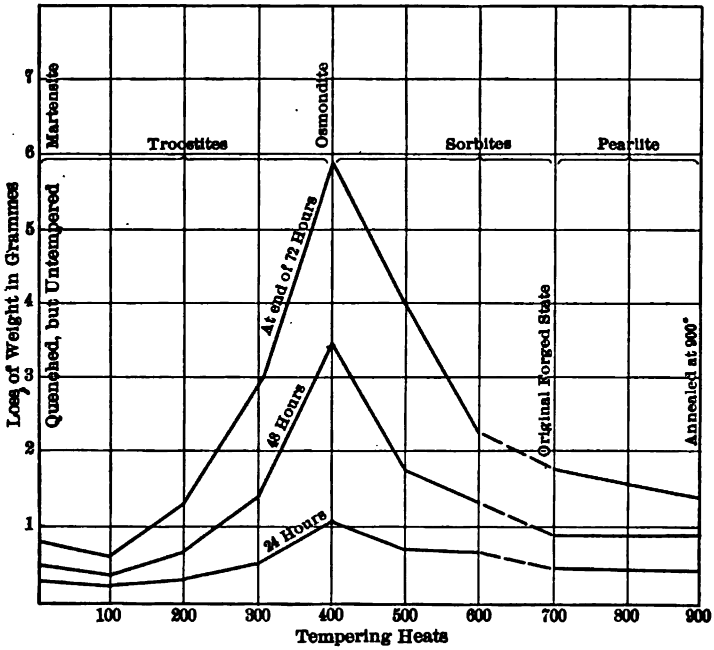

FIG. 283.—Effect of Various Tempering Heats on the Solubility of 0.95 per cent Carbon Tool Steel, Heated to 900° C. and Tempered by Reheating to the Temperature Indicated. (Heyn and Bauer.)

The diagrams reproduced in Figs. 283 and 284 * indicate the relative corrodibility of a 0.95-per-cent-carbon tool steel and a 0.07-per-cent-carbon mild steel, respectively, when subjected to the action of a 1-per-cent solution of sulphuric acid, after the various heat treatments indicated.

A study of Fig. 283 indicates that a tool steel is least corrodible when in a glass-hard condition, reheating not having been carried above

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* These tests are quoted by Cushman and Gardner from the studies of Heyn and Bauer, originally published in the Jour. Iron and Steel Inst., May 1, 1909.

100° C. Further heating increases the solubility in acid until a maximum solubility is reached when the tempering heat is 400° C. Higher temperature heats again reduce solubility until a minimum solubility, about twice that of the hardened steel, is attained when the metal has been completely annealed at 900° C.

Fig. 284 indicates that the solubility of a very mild steel is increased as the temperature of tempering increases; a maximum solubility is reached

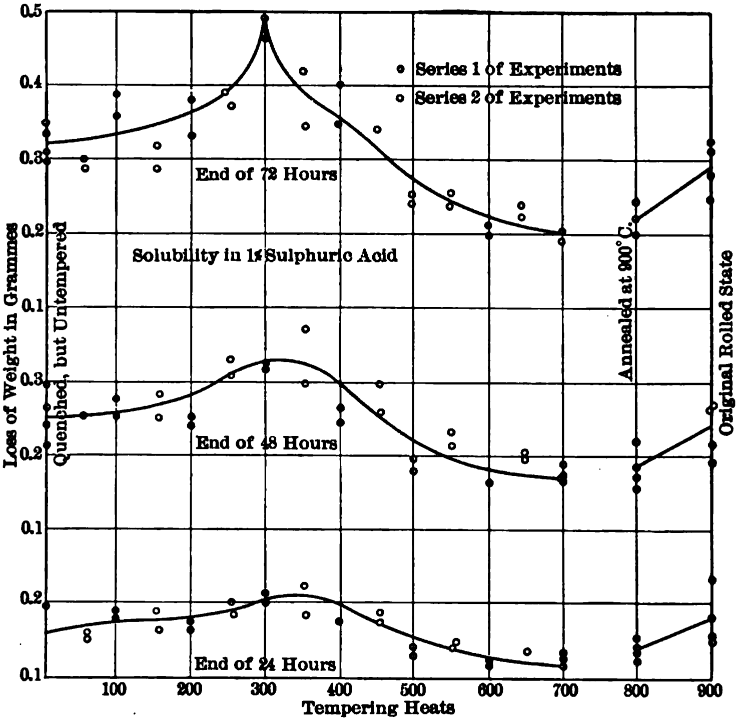

FIG. 284.—Effects of Various Tempering Heats on the Solubility of 0.07 per cent Cqrbon Mild Steel, Quenched at 1000–1030° C. and Tempered by Reheating to the Temperature Indicated. (Heyn and Bauer.)

when reheating is carried to about 300° C.; and higher heats again reduce solubility, until, when the steel is completely annealed at 900° C., the solubility is considerably below that of both the original rolled bar and the steel after hardening but without tempering. Attention is directed to the fact that a comparison of Figs. 283 and 284 will show that the tool steel is about 120 times as soluble as the mild steel when reheated to the temperature which produces maximum solubility, about 60 times as soluble in the original or the annealed condition, and about 25 times as soluble when hardened but not tempered. (This comparison is based upon the comparative loss in weight of the two steels after seventy-two hours.) This comparison would seem to mean that a large increase in carbon content enormously increases the corrodibility of steels in acid solutions.

The effect of that form of cold working involved in the drawing of mild steel wire upon the solubility of the material in 1 per cent sulphuric acid is indicated by Fig. 285. It appears that cold working increases the solubility of the steel to a considerable extent, a maximum solubility being reached, however, when the ratio of elongation is about four (wire about four times its original length).

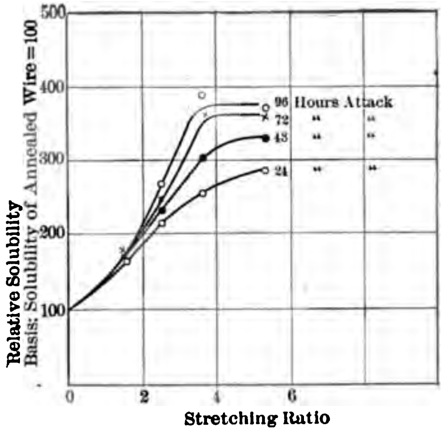

FIG. 285.—Influence of Cold-Drawing on the Solubility of Mild Steel Wire. (Heyn and Bauer.)

The results of two quite recent series of corrosion tests, in which the test specimens were exposed only to the action of such atmospheric corrosive media as may be encountered by iron and steel used structurally, is presented by the curves of Fig. 286. This series of curves is based upon tests made by Mr. A. W. Carpenter,* begun in 1911, and still in progress (1914).

The various classes of iron and steel described on Fig. 286 were subjected to the corrosive action of the locomotive gases existing in the central portion of the Weehawken tunnel (which is about 4300 feet long), and similar specimens were subjected to atmospheric exposure on the roof of an office building. In plotting the curves from the tabulated data obtained in the first series of tests the author has taken the liberty of wholly disregarding the results recorded at the end of the first 178-days' exposure, although the corrosion loss reported is indicated. This procedure is justified in a measure by the fact that, while the extent of acidity of the tunnel atmosphere was quite variable at all times, the strength of the corrosive action was especially changed during the period between the 118-day and the 178-day observations by the setting up of a blower at one end of the tunnel for the purpose of clearing some of the gases. It would appear from the corrosion losses observed during

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* Proc. Am. Soc. Test. Matrls., Vol. 13, p. 617.

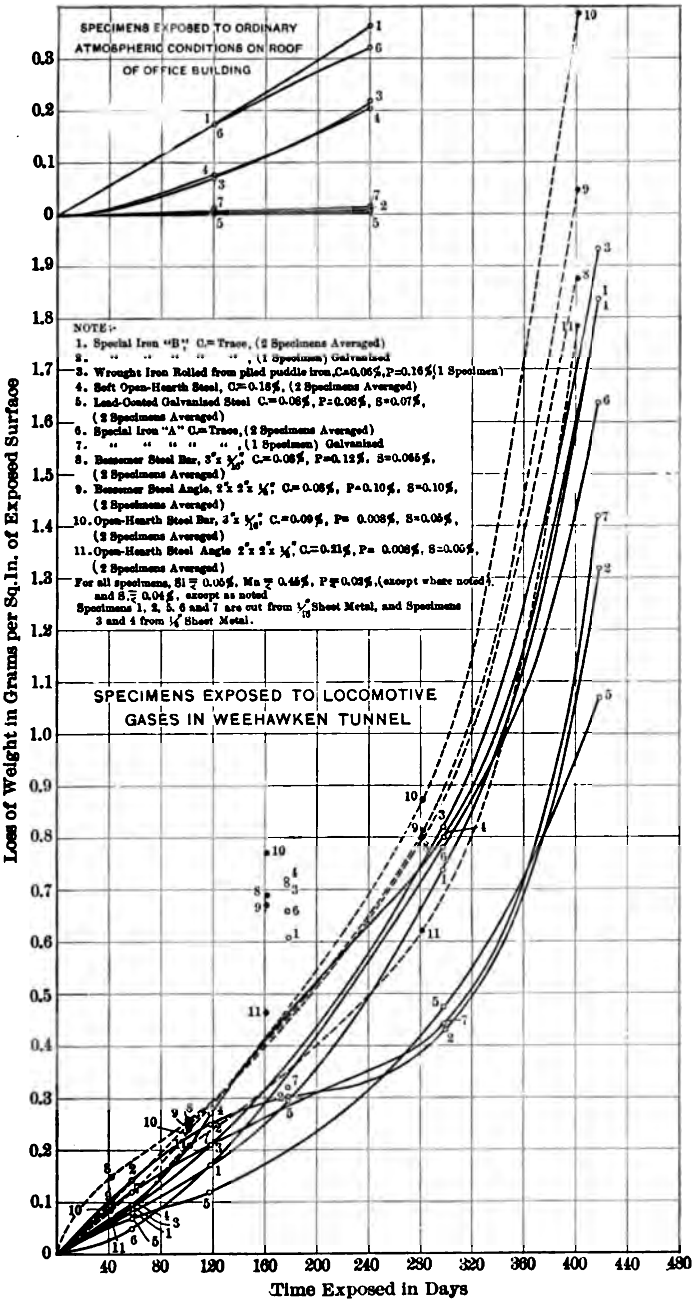

FIG. 286.—Relative Corrosion of Various Irons and Steels. (Carpenter.)

subsequent periods that this expedient may have increased corrosion, by causing more movement of the gases, instead of having the desired effect.

The somewhat inaccurate method of making these tests, particularly the fact that the average acidity of the atmosphere doubtless varied considerably during different exposure periods, is wholly responsible for the lack of uniformity exhibited by the curves. On account of this lack of accuracy, generalizations from the test results must be made with caution. It may be pointed out, however, that the wrought irons do not appear to any advantage when compared with the mild steels, except that they do excel the structural grades of steel tested in the form of bars and angles. The protective coating of lead or zinc appears to be only moderately effective in retarding corrosion under the conditions of exposure of these tests.

The series of tests made by exposure of the same specimens to the action of atmospheric agencies on the roof of an office building, exhibit somewhat more uniform results than those made by exposure in the tunnel. The results thus far reported are not sufficiently extensive to warrant rigid conclusions, but it is interesting to note that the corrosion of the very pure wrought irons is nearly double that of the impure wrought iron and the mild steel, while the corrosion of the lead and zinc-coated specimens is practically negligible after about eight months' exposure.

The relative extent to which corrosive action proceeds in various corrosive media is indicated by the curves of Fig. 287. These curves are based upon a series of tests reported by the Water Service Committee of the American Railway Engineering Association.* The test specimens used in this instance were bits of sheet metal $\frac{1}{8}$ inch thick, 2 inches wide and 2 to 3 inches long. With the exception of specimens 6 and 7 the surfaces were cleaned of all adhering scale, etc., and were filed bright before being tested.

The various corrosive media employed are described in a general way as follows:

The alkaline water was cooling water in the overflow tank from the furnace water jackets of a copper smeltery. Its alkalinity in $CaCO_3$ was 21 parts in 100,000, and its total content of sodium-carbonate, sulphate, and chloride was 56 per cent.

The cinders were derived from bituminous coal and contained, as its principal constituents, 24.60 per cent fixed carbon, 24.76 per cent Al_2O_3, 41.06 per cent SiO_2, and 5.44 per cent volatile matter.

The clean sand contained 82.31 per cent SiO_2, 9.44 per cent Al_2O_3,

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* Engineering News, Vol. 72, p. 255, July 30, 1914.

3.18 per cent alkalies, 2.98 per cent Fe_2O_3, and 2.31 per cent of lime and magnesia.

The clay soil was mixed with 5 per cent salt by weight. The resultant composition was SiO_2—54.34 per cent, alkalies—10.17 per cent, $Al_2O_3+Fe_2O_3$—18.04 per cent, $CaO+MgO$—7.25 per cent, H_2SO_4—0.95 per cent, H_2CO_3—2.05 per cent, P_2O_5—0.16 per cent, and Cl—2.83 per cent.

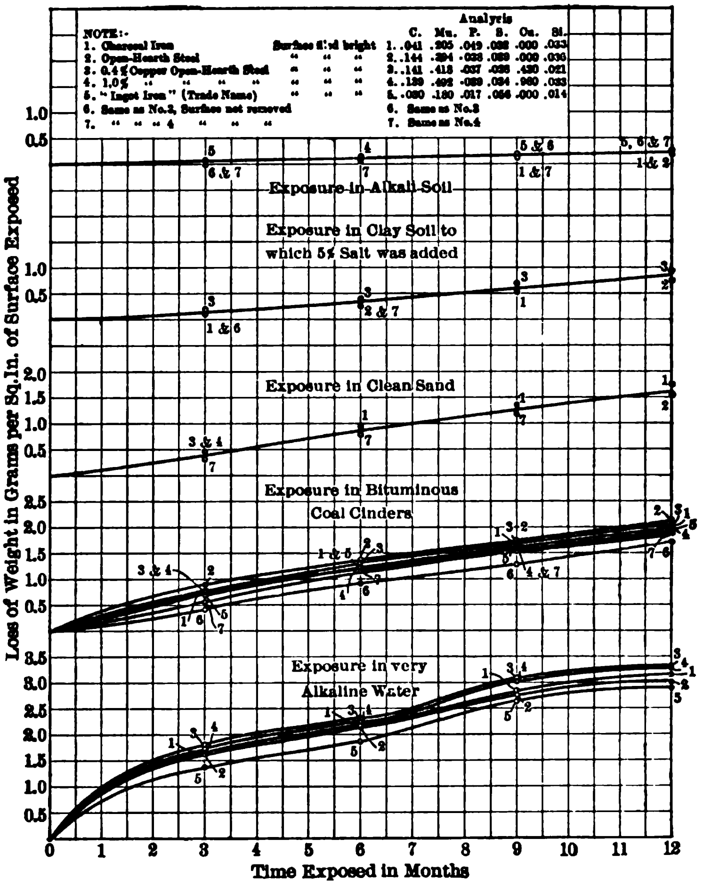

FIG. 287.—Corrosion of Iron and Steels in Various Corrosive Media. (Water Service Committee, Amer. Ry. Eng. Assoc.)

The alkali soil was a mixture of equal parts of white and black alkali soils, the composition of the mixture being SiO_2—48.46 per cent, alkalies—11.10 per cent, $Al_2O_3+Fe_2O_3$—10.76 per cent, $CaO+MgO$—10.82

per cent, H_2SO_4—9.64 per cent, H_2CO_3—2.26 per cent, P_2O_5—0.06 per cent, and Cl—3.64 per cent.

The test specimens were in all cases immersed or buried in the corrosive medium, the latter being contained in aluminum pans which were exposed to outdoor air and sunlight. In the case of all tests except those employing alkaline water, the materials in the pans were periodically saturated with water and allowed to become comparatively dry, the idea being to duplicate in a general way the service conditions of iron and steel buried to a slight depth in earth.

The most surprising result of these tests is the fact that the various classes of iron and steel behave very nearly alike in all the corrosive media. On this account, and the consequent difficulty experienced in showing distinct curves for all materials used, the author has shown simply the average curve in Fig. 287 in a number of cases, the maximum and minimum corrosion being indicated by circles only.

The relative extent of the corrosive action in the various media is not surprising, with the exception of the cases of the relative corrosion in clean sand, and in the clay and salt and the alkaline soil mixtures. The experimenters explain this circumstance in part by the statement that " the sand is porous and allows a comparatively free circulation of air (whereas) the clay and alkali soils are very close-grained and practically exclude the air."

(Attention is called to the fact that the scale of ordinates of Fig. 287 is ten times that of Fig. 286, and the relative corrosion of the irons and steels tested by Carpenter, and those tested by the Committee of the Railway Engineering Association, indicates that all of the corrosive media employed by the latter, with the exception of the clay and the alkali soils, were much more potent than the gases in the railway tunnel.)

499. Allowable Unit Stresses for Steels. The following table is a summary of the allowable unit stresses for steels prescribed in various specifications and building codes of a number of cities. In the first column the design value most commonly prescribed and used is given; the second column gives the maximum value permitted in ordinary good practice, and the third column gives the minimum value used in most conservative design.

ALLOWABLE UNIT STRESSES FOR STEELS

Character of Stress	Material.	Working Stress.		
		Usual. Lbs. per Sq. In.	Maximum. Lbs. per Sq. In.	Minimum. Lbs. per Sq. In.
Tension	Rolled steel	16,000	17,500	14,500
	Cast Steel	16,000	16,500	12,000
Compression (short blocks)	Rolled Steel	16,000	16,500	14,500
	Cast Steel	16,000	16,250	12,000
Shear	Shop rivets	10,000	12,000	8,750
	Pins	10,000	12,000	8,750
	Webs of beams	10,000	12,000	8,750
	Field rivets	9,000	10,000	8,000
	Field bolts	7,500	8,750	8,000
Bearing	Rivets and pins	20,000	20,000	18,000
	Field rivets	18,000	20,000	15,000
Extreme fiber stress, bending	Rolled beams	16,000	16,000	14,500
	Riveted beams	16,000	16,000	12,000
	Pins	20,000	20,000	16,000

500. Production of Steel in the United States. Statistics. The following table, which has been abstracted from "Mineral Resources of the United States," gives the statistics of production of various steels for the years 1900 to 1913 inclusive:

PRODUCTION OF STEEL IN THE UNITED STATES, 1900–1913.
LONG TONS

Year.	Class of Steel.				Total.
	Bessemer.	Open Hearth.	Crucible.	Other Steel.	
1900	6,684,770	3,398,135	100,562	4,862	10,188,329
1901	8,713,302	4,656,309	98,513	5,471	13,473,595
1902	9,138,363	5,687,729	112,772	8,386	14,947,250
1903	8,592,829	5,829,911	102,434	9,804	14,534,978
1904	7,859,140	5,908,166	83,391	9,190	13,859,887
1905	10,941,375	8,971,376	102,233	8,963	20,023,947
1906	12,275,830	10,980,413	127,513	14,380	23,398,136
1907	11,667,549	11,549,736	131,234	14,075	23,362,594
1908	6,116,755	7,836,729	63,631	6,132	14,023,247
1909	9,330,783	14,493,936	107,355	22,947	23,955,021
1910	9,412,772	16,504,509	122,303	55,335	26,094,919
1911	7,947,854	15,598,650	97,653	31,949	23,676,106
1912	10,327,901	20,780,723	121,517	21,162	31,251,303
1913	9,545,706	21,599,931	121,226	34,011	31,300,874

CHAPTER XVI

THE SPECIAL ALLOY STEELS

501. General. Definition and Classification of Alloy Steels. The Committee on Uniform Nomenclature of Iron and Steel of the International Association for Testing Materials defines *alloy steel* as " steel which owes its distinctive properties chiefly to some element or elements other than carbon, or jointly to such other element and carbon." *Ternary alloys*, or three-part alloys, are those whose properties are chiefly dependent upon the presence of one element other than iron and carbon. *Quaternary alloys* contain two influential elements other than iron and carbon.

The development of alloy steels which has characterized the last twenty-five years has entirely revolutionized the practice of manufacture and use of tool steels, has wrought great change in the making of machine, automobile, armor plate, and ordinance steels, and has even had a considerable influence upon structural steels used primarily in the construction of bridges and buildings. The study of alloy steels in general is one of great complexity, however, and in the consideration of the subject which follows no exhaustive treatment will be attempted. Each of the principal classes of alloy steels will be briefly described, its predominant characteristics noted and some applications mentioned.

All alloy steels bear names which indicate the nature of the alloying element present. The principal classes of alloy steels are those listed below:

Ternary Alloys
Nickel steel
Manganese steel
Chrome steel
Tungsten steel
Molybdenum steel
Silicon steel
Vanadium steel
Etc.

Quaternary Alloys
Nickel-chromium steel
Chromium-manganese steel
Tungsten-chromium steel
Nickel-manganese steel
Nickel-vanadium steel
Nickel-tungsten steel
Nickel-silicon steel
Tungsten-manganese steel
Manganese-silicon steel
Etc.

TERNARY ALLOYS

502. Nickel Steel. Nickel steel usually contains between 2.25 and 4.5 per cent of nickel together with from 0.15 to 0.4 per cent of carbon. This class of alloy steel combines great tensile strength and hardness with a very high elastic limit, great ductility, toughness, and relatively high resistance to corrosion. Certain very special nickel steels are also remarkable for their low coefficients of temperature expansion, such as that containing 36 per cent nickel (patented under the name "Invar"), whose coefficient approaches zero, and that containing 42 per cent nickel (patented under the name "Platinite"), which at ordinary temperatures has about the same coefficient as glass.

Critical Changes and Irreversible Transformations.[*] The presence of nickel in varying amounts was found by Waterhouse to have an important effect upon the position of the critical points (Ar_1, Ar_2, Ar_3) in cooling, although the mode of occurrence of these points was not changed. 3.8 per cent of nickel was found to lower the position of the critical points about 75° C., and as nickel is increased this effect becomes more pronounced until with 25 per cent of nickel the critical range is below atmospheric temperatures, i.e., the steel would have to be cooled below atmospheric temperatures in order to change it from the gamma form in which it exists to the beta and alpha modifications.

With less than 25 per cent of nickel these steels are "irreversible," i.e., the changes which take place in cooling through a certain range are not reversed by heating through the same range. With 20 per cent of nickel the critical range is below 100° C., and the changes accomplished by cooling below this point are not reversed upon heating until a temperature of nearly 600° C. is reached. Irreversibility is most marked with steels containing between 12 and 25 per cent of nickel, and when the nickel content exceeds about 40 per cent it becomes reversible like ordinary steels.

Tensile Properties. The general nature of the effect of the presence of from 2.25 to 4.5 per cent of nickel upon the tensile properties of steel has been stated to be a great raising of the strength and elastic limit without sacrificing ductility. It will now be shown that the characteristic properties of a given nickel steel are not solely dependent upon the amount of nickel present, but that the carbon content and the heat treatment of the steel are very influential factors.

Fig. 288 presents the results obtained by M. Albert M. Portevin[†]

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[*] See papers of G. B. Waterhouse and L. Dumas in Jour. Iron and Steel Inst., 1905, Vol. 2.

[†] "Contribution to the Study of the Special Ternary Steels," Iron and Steel Institute, Carnegie Scholarship Memoirs, Vol. 1, 1909, p. 230.

in an investigation of the tensile properties and shearing strengths of nickel steels of varying carbon content. (The author is responsible for the conversion of strength values to English units and the construction of the diagram.)

Fig. 289 presents the results obtained by Mr. Walter Giesen * in a similar study of almost the same scope. These two wholly independent investigations are both reported herein because both exhibit certain features in common, and the conclusions which may be arrived at are given additional importance by being based upon two independent studies of the problem.

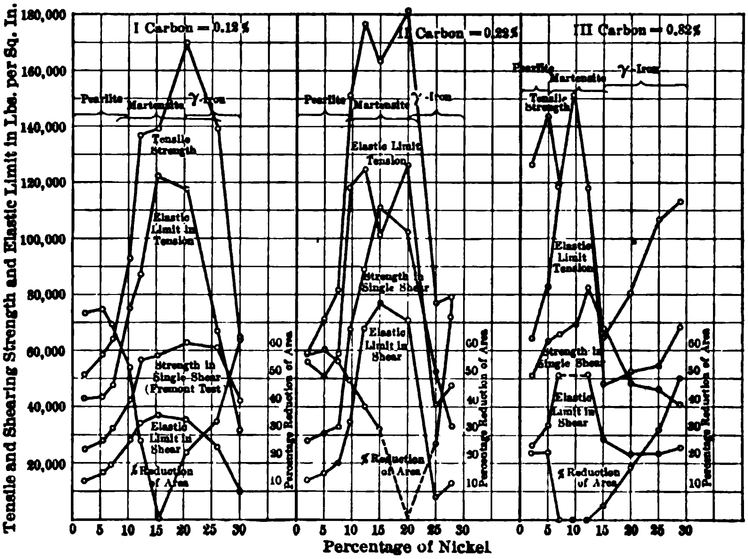

Fig. 288.—Tensile Properties and Shearing Strength of Various Nickel Steels (Portevin.)

The steels tested by M. Portevin, Fig. 288, were annealed before testing by heating for three hours at 850° C. Those of Mr. Giesen, Fig. 289, were annealed by heating to 850° C., followed by slow cooling during a period of about eighteen hours.

A study of these two diagrams appears to justify the following general conclusions:

Low-carbon Steels. 0.012 and 0.015 Per Cent Carbon

Tensile strength increases fairly uniformly with increase in nickel content until a maximum of 170,000 to 185,000 pounds per square inch

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* "The Special Steels in Theory and Practice," Carnegie Scholarship Memoirs, Vol. 1, 1909, p. 1.

is reached with 20 to 25 per cent. nickel. With higher nickel content the strength decreases rapidly until, with 30 or 35 per cent present, the strength is nearly equal to the strength of 5-per-cent-nickel steel, i.e., about 60,000 to 75,000 pounds per square inch.

The elastic limit varies with the nickel content in approximately the same manner. Until its maximum value of 120,000 to 150,000 pounds per square inch is reached with 15 to 20 per cent nickel present, it remains equal to about 80 to 85 per cent of the tensile strength. With higher nickel content the elastic limit decreases rapidly, and with 30 to 35 per cent nickel is somewhat lower than it is with only 5 per cent nickel.

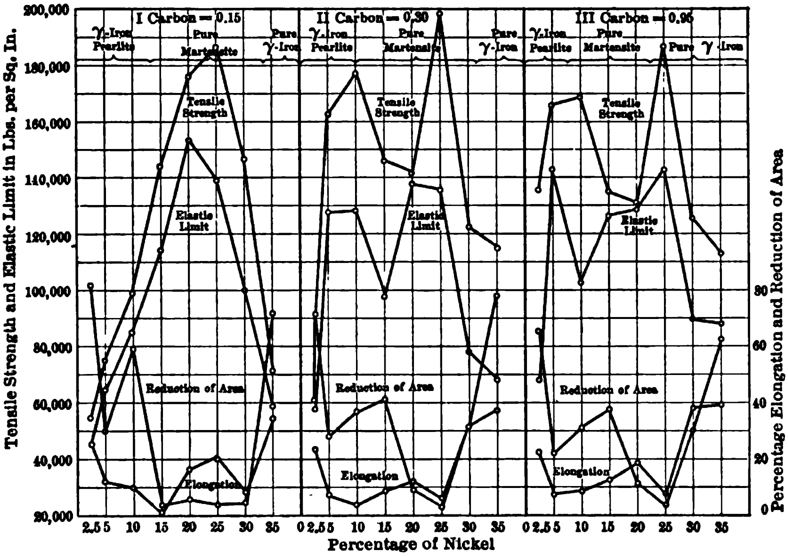

FIG. 289.—Tensile Properties of Various Nickel Steels. (Giesen.)

The ductility, as indicated by the elongation and contraction of area, is very considerable with only about 2.5 to 5 per cent nickel present. It decreases very rapidly with increase in nickel, however, until when about 15 per cent is present, the steel is absolutely non-ductile. This, doubtless, is due to the fact that with increase in nickel the steel changes from the normal pearlite condition to the martensitic form, in which state it is very brittle. With further increases in nickel content an increasing proportion of γ-iron replaces martensite; ductility is therefore gradually restored, and the 30- or 35-per-cent-nickel steel is nearly as ductile as the steel containing only 2.5 per cent nickel.

Medium-carbon Steels. 0.22 and 0.30 Per Cent Carbon

The tensile strength and elastic limit of medium-carbon steels are greatly increased by percentages of nickel not exceeding 10 or 12 per cent. Between these steels and ones containing from 20 to 25 per cent of nickel the strength suffers, owing to extreme brittleness of the martensitic steel. With about 20 to 25 per cent nickel the strength appears to be momentarily restored, presumably because of the relief of brittleness by reason of the appearance of γ-iron with the martensite, but as the γ-iron proportion increases with further increases in nickel the strength again falls off rapidly. The variation of the ductility with increasing nickel content is just the reverse of the variation of the strength and elastic limit.

High-carbon Steels. 0.82 and 0.95 Per Cent Carbon

The tests of the two high-carbon steels quoted are not in as close agreement as are the tests of low- and medium-carbon steels, but certain points are nevertheless worth noting.

The strength of the high-carbon steel containing 2.5 per cent nickel is extremely high (125,000 to 135,000 pounds per square inch) as compared with that of the corresponding medium- and low-carbon steels. Brittle martensitic steel is encountered with between 5 or 10, and 20 or 25 per cent nickel present, the strength being recovered to a greater or lesser degree with about 25 per cent nickel. The extreme brittleness of the 0.82-per-cent-carbon steel of Portevin is illustrated by the coincidence of the elastic limit and the ultimate strength (zero ductility) in the cases of the three steels containing between 7 and 13 per cent carbon.

Giesen states that the brittle zone (minimum ductility) was found to be located as follows for a series of high-carbon nickel steels:

In steel with 0.28 per cent carbon	at 14.0 per cent nickel.
0.87	8.9
0.98	8.8
0.98	8.3
1.00	8.0
1.12	7.8
1.21	6.5
1.28	5.1
1.30	2.3

The shearing strength exhibited by the curves of Fig. 288 follow the same law of variation as the tensile strengths except that the shearing strength (as determined by the Fremont method) appears to be less affected by brittleness than is the tensile strength. Note that these shear values were obtained by testing specimens in single shear, not double shear.

The nickel steels considered in the above paragraphs were all (with the exception of one or two) characterized by the presence of more nickel than is present in the common or structural grades, in which the nickel content is rarely permitted to exceed about 3.5 per cent. The following discussion will be concerned wholly with nickel steels whose nickel content is in the neighborhood of 3 per cent.

In Fig. 290 the author has summarized the results of a very remarkable investigation of the properties of 3 per cent nickel steels made by Messrs. Andrew McWilliam and Ernest J. Barnes of the University of Sheffield.* An effort has been made to make the diagram self explanatory, and not all of the details of the results of the tests expressed thereby will be discussed.

Relation of Tensile Strength and Yield Point to Carbon Content and Heat Treatment

The tensile strength and yield point increase rapidly, whatever the heat treatment (except annealing), as the carbon content increases. The relative extent to which various heat treatments affect the strength and yield-point is indicated by a comparison between the various curves and the curve for the normalized steel.

The normalized steel shows a tensile strength of 59,400 pounds per square inch for the steel of lowest carbon content (0.06 per cent carbon), and 133,200 pounds per square inch for the steel of highest carbon content (0.91 per cent carbon). The corresponding values of the yield-point for the same steels are 42,000 pounds per square inch, and 68,000 pounds per square inch, respectively.

Quenching at 850° C., followed by annealing at 400° C., gives the strongest steel for all carbon contents, the strength being 66,200 pounds per square inch for the 0.06 per cent carbon steel and 211,400 pounds per square inch for the 0.91 per cent carbon steel. The corresponding values of the yield-point are 52,800 and 188,000 pounds per square inch, respectively.

Quenching at 850° C., followed by tempering at 500° C., is slightly less beneficial to strength and raises the yield-point less than does tempering at 400° C., and especially so for the steels of higher carbon content.

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* "Some Properties of Heat-Treated Three Per Cent Nickel Steels." Jour. Iron and Steel Inst., Vol. 83, 1911, p. 269.

The strengths corresponding to those above quoted for the steels of lowest and highest carbon content, respectively, are 63,400 and 177,400 pounds

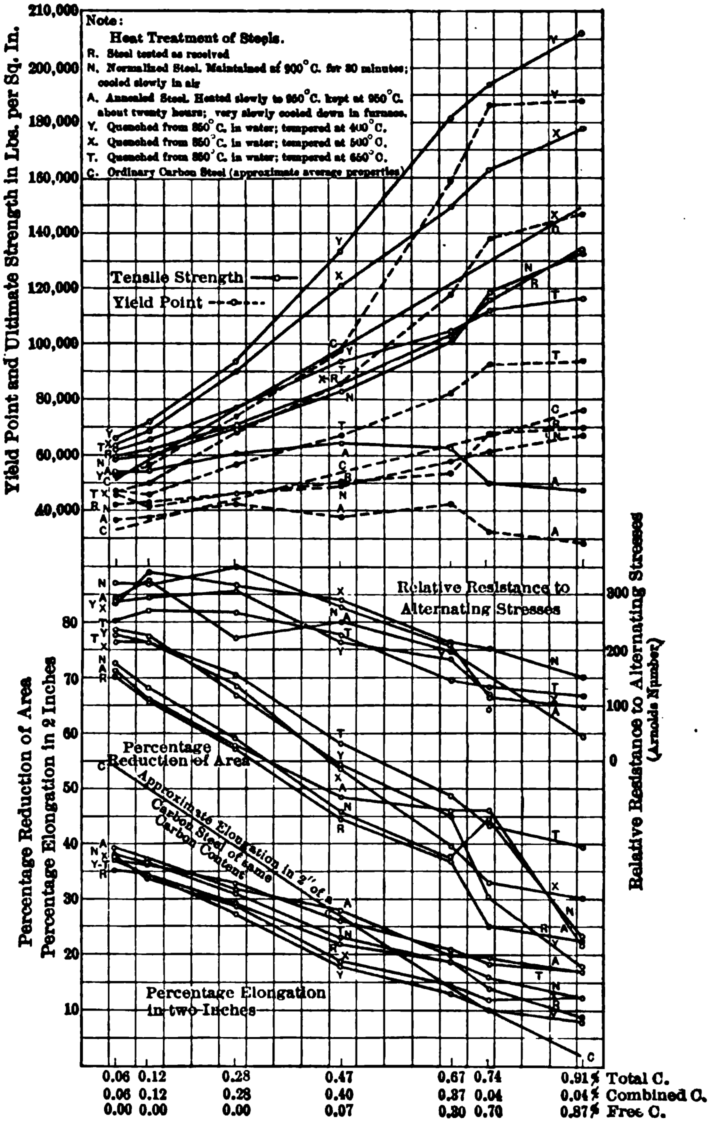

FIG. 290.—Properties of 3-per-cent-Nickel Steels with Various Carbon Contents and Various Heat Treatments. (McWilliam and Barnes.)

per square inch, the corresponding yield-point being 46,400 and 147,200 pounds per square inch, respectively.

Quenching at 850° C., followed by tempering at 650° C., is only slightly beneficial to strength in the case of the low- and medium-carbon steels, and reduces the strength of high-carbon steels below that of the normalized steel. The yield-point is somewhat raised for all of the steels.

The drastic annealing treatment is very detrimental to the strength of all steels, and invariably lowers the yield-point as well. The injurious effect of annealing becomes more marked as the carbon percentage increases.

Relation of Ductility to Carbon Content and Heat Treatment

The ductility, as indicated by the percentage elongation and the percentage reduction of area, is inversely proportional to the carbon content.

The effect of the various heat treatments upon ductility is not shown to be a constant for steels of different carbon contents. In general, the annealing treatment and tempering at 650° C., after hardening, have the most pronounced tendency to promote ductility, and the hardened steels which are tempered at low heats are least ductile.

Relative Resistance to Alternating Stresses with Various Carbon Contents and Heat Treatments

The resistance of nickel steels to failure under repeated stresses, alternating in a cycle from tension to compression, appears to increase with the carbon content up to about 0.3 per cent carbon, and thereafter decreases as the carbon content is further increased.

The effect of annealing, or hardening followed by moderate tempering, appears to be generally a slight decrease in the resistance to fatigue failure in the case of low- and medium-carbon steels, but a pronounced injury is noted in the case of high-carbon steels. Tempering at a high temperature after annealing reduces the fatigue resistance of all steels considerably.

The curves marked *C* * have been added to the diagram of Fig. 290 by the author in order to afford a rough comparison of the strength, yield-point, and elastic limit of these nickel steels with an ordinary steel of corresponding carbon content. It appears that the hardened and tempered nickel steels excel carbon steels very considerably in tensile strength, and the yield-point of the former is very much higher than that of carbon steels which have not been heat-treated. In the absence of any heat treatment, or when the nickel steel is annealed, it appears to be inferior to the ordinary carbon steel tested as rolled.

* These curves are based upon the Watertown Arsenal Tests quoted in Art. 487.

The ductility of nickel steels of low-carbon content also appears to be below that of ordinary carbon steel, but high-carbon nickel steels greatly exceed ordinary high-carbon steels in ductility.

The comparison of the tensile properties of nickel steel with those of carbon steel just drawn must be accepted with caution, and must not be given too great weight. The two sets of test data are doubtless not strictly comparable, because the tests were made under different circumstances, with steels which may not have been at all similar except in carbon content, and with test specimens which were far from being alike as to dimensions. Nevertheless, it has been considered desirable to present this comparison because of the author's conviction that carbon steels, when proper attention is given to the details of their manufacture and treatment, are not excelled in tensile properties by nickel steels.* It may be a fact, however, that nickel steels made with only ordinary care, and none too skillfully heat-treated, may excel carbon steels made under the same conditions.

Impact Strength. The superior ability of nickel steels to resist distortion and rupture under impact is considered one of their most valuable attributes. Only rather meager data exist, however, which afford an opportunity to compare the relative behavior of carbon steel and nickel steel in this respect. The following data are quoted

	No. of Tests.	Structural Carbon Steel.			No. of Tests.	3.5% Nickel Steel.		
		Average.	Maximum.	Minimum.		Averages.	Maximum.	Minimum.
Impact Tension.								
Per cent elongation............	5	31.5	32.0	31.0	4	16.5	19.0	13.0
Per cent contraction of area.....	5	58.9	60.8	57.0	4	49.7	54.0	45.0
Rupture-work, ft.-lbs. per cu.in. .	5	1736.0	1910.0	1540.0	3	2198.0	2300.0	1960.0
Impact Flexure (Plain Bars)								
Deflection at blow from 3 ins., ins.	8	0.18	0.21	0.16	5	0.09	0.11	0.09
Deflection at elastic limit, ins....	8	0.21	0.23	0.16	5	0.26	0.30	0.22
Height of drop at elas. limit, ins..	8	3.70	3.50	3.00	5	8.10	9.00	7.25
Impact Flexure (Nicked Bars)								
Deflection at blow from 3 ins., ins.	3	0.20	0.22	0.17	3	0.12	0.14	0.12
Deflection at elastic limit, ins....	3	0.21	0.25	0.17	3	0.23	0.24	0.21
Deflection at rupture, ins........	3	1.23	1.40	0.90	3	0.62	0.70	0.57
Height of drop at elas. limit, ins..	3	3.30	3.37	3.25	3	6.10	6.25	6.00
Height of drop at rupture, ins....	3	11.10	12.75	9.50	3	15.60	17.00	14.50

NOTE: The drop hammer used weighed 55 pounds; the first drop was from a height of ½ inch, and succeeding drops were from heights increased ½ inch each time. The span of the flexure specimens was 18 inches. Their dimensions are not stated.

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* For a discussion of this question from the opposite point of view the reader is referred to the paper of Mr. J. A. L. Waddell, "Nickel Steel for Bridges," published in Trans. Am. Soc. C.E., Vol. 63, 1909, p. 375.

from tests made by Professor W. K. Hatt in connection with an investigation of the properties of nickel steel made by Mr. J. A. L. Waddell.* The tests were made in the manner described in Art. 495 above. Unfortunately, no information is given concerning the analysis or the treatment of either of the steels.

The above table " shows that, in the impact tension tests, while the elongation of carbon steel was nearly twice as great as that of nickel steel and the contraction was more than 20 per cent greater, nickel steel had a resilience 26 per cent higher than carbon steel. . . ." Also, " the impact flexure on plain bars shows an increase in resilience of nickel steel over carbon steel equal to 120 per cent at the elastic limit, and in the case of nicked bars an increase of 85 per cent at the elastic limit and 40 per cent at the point of rupture."

Magnetic Properties. The magnetic properties of three commercial nickel steels, as determined by Messrs. E. Colver-Glauert and S. Hilpert,† are exhibited by Figs. 291, 292 and 293.

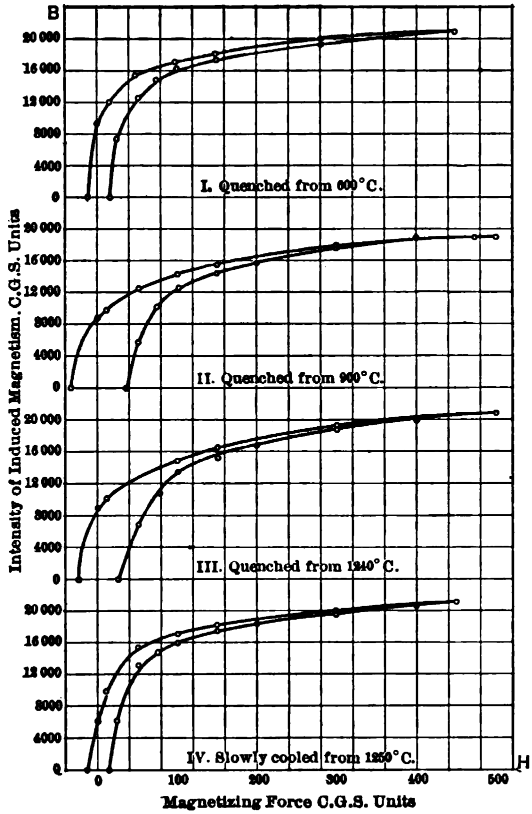

FIG. 291.—Magnetic Properties of 5-per-cent-Nickel Steel. (Colver-Glauert and Hilpert.)

The steel used in the series of tests, the results of which are represented by Fig. 291, contained 5.86 per cent nickel and 0.37 per cent carbon; Fig. 292 represents the results obtained with a steel containing 24.32 per cent nickel and 0.24 per cent carbon; and Fig. 293 the results obtained with a steel containing 32.90 per cent nickel and 0.30 per cent carbon. The constituents other than nickel

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* Trans. Am. Soc. C.E., Vol. 63, 1909, p. 110.

† Jour. Iron and Steel Inst., Vol. 83, 1911, p. 375.

and carbon were present in so nearly constant small amounts that they need not be taken account of.

A comparison of curves *I*, *II*, *III* and *IV*, Fig. 291, reveals the fact that the intensity of magnetism induced in a 5-per-cent-nickel steel by a given magnetizing force is subject to great variation with different heat treatments. The least permeable steel is that quenched from 900° C., and quenching from 1240° C., only slightly improves the permeability. Quenching from 600° C., or slow cooling from 1250° C., renders the steel considerably more permeable. All of these heat treatments affect the hysteresis loss in the same way that permeability is affected. Cooling these steels to low temperatures does not in any way affect their magnetic properties.

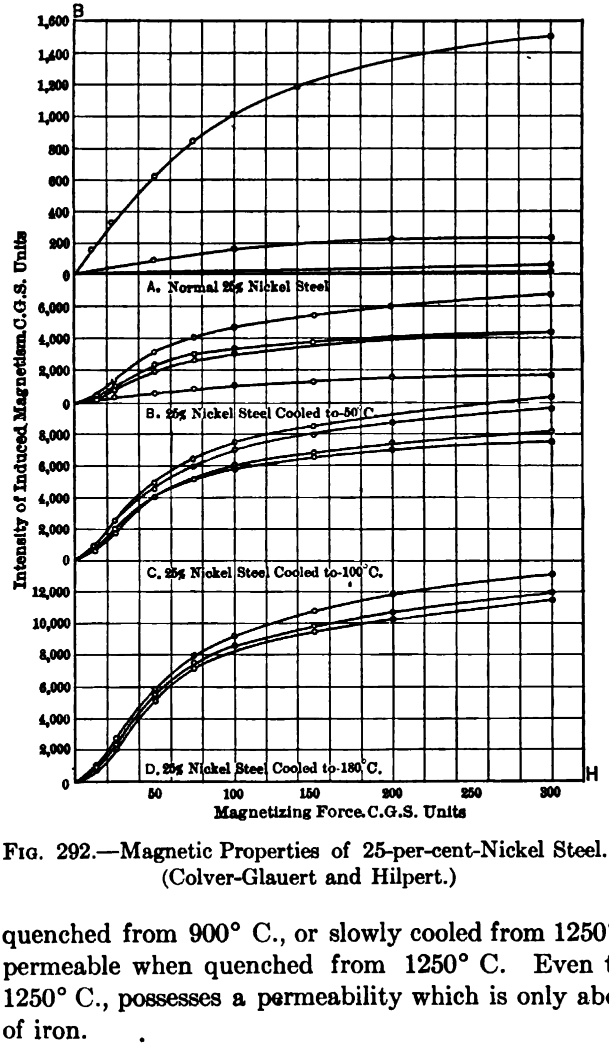

FIG. 292.—Magnetic Properties of 25-per-cent-Nickel Steel. (Colver-Glauert and Hilpert.)

The corresponding curves of Fig. 292 (*a*) show that the 25-per-cent-nickel steel is magnetically impermeable when quenched from 600° C., almost completely impermeable when quenched from 900° C., or slowly cooled from 1250° C., and only slightly permeable when quenched from 1250° C. Even the steel quenched at 1250° C., possesses a permeability which is only about one-fifteenth that of iron.

Cooling the hardened or annealed 25-per-cent-nickel steel below zero has a remarkable effect in increasing permeability. This fact is exhibited by the induction curves of Fig. 292 (*b*), Fig. 292 (*c*), and Fig.

292 (*d*), which have been derived from steels cooled to −50° C., −100° C., and −180° C., respectively. Even the extreme cooling to −180° C., raises the intensity of induced magnetism to only about six-tenths that of the 5-per-cent-nickel steel,. however.

Fig. 293 exhibits the magnetic property of the 33-per-cent-nickel steel. It will be noted that the maximum intensity of induced magnetism is about one-half that of the 5-per-cent-nickel steel, that the hysteresis loss is extremely low, and that the various heat treatments only slightly affect magnetic properties. Low temperatures do not affect these steels magnetically.

Corrodibility. The relative corrodibility of three nickel steels and a 0.29-per-cent-carbon steel in various media is exhibited by the curves of Fig. 294. This diagram has been prepared from the data secured in a study of the problem made by Messrs. J. N. Friend, J. L. Bentley and W. West.*

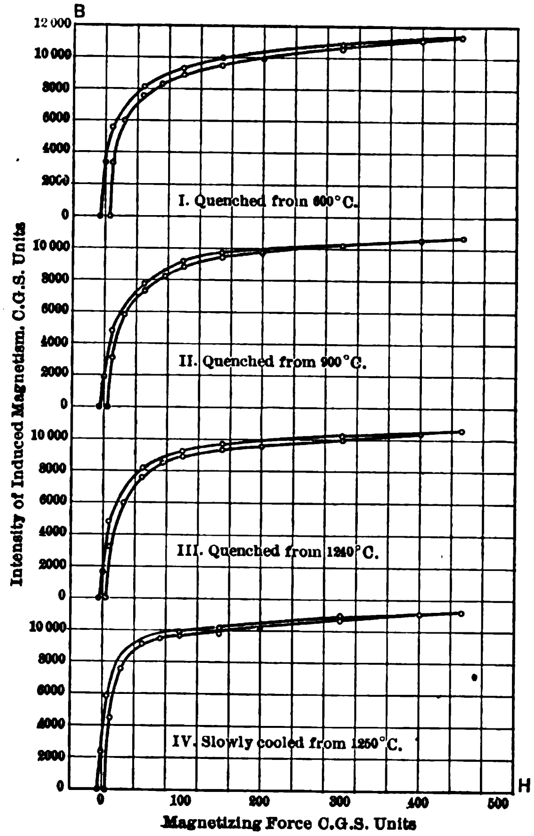

FIG. 293.—Magnetic Properties of 33-per-cent-Nickel Steel. (Colver-Glauert and Hilpert.)

The specimens used in this series of tests were cylindrical discs 0.7 centimeters thick and 2.8 centimeters in diameter. They were exposed to the various corroding media while lying flatwise on a sheet of paraffin wax in the bottom of a glass crystallizing dish. (Note that the diagram does not express actual corrosion loss, but does express simply the ratio of the loss in weight of the nickel-steel specimen in a given medium to the loss in weight of a 0.29-per-cent-carbon-steel specimen exposed in the same medium.)

* Proc. Iron and Steel Inst., Vol. 85, p. 249, and Vol. 87, p. 388, 1912, 1913.

The comparative corrodibility of the various nickel steels and the carbon steel, under the influence of the several media employed, is thus expressed by the diagram:

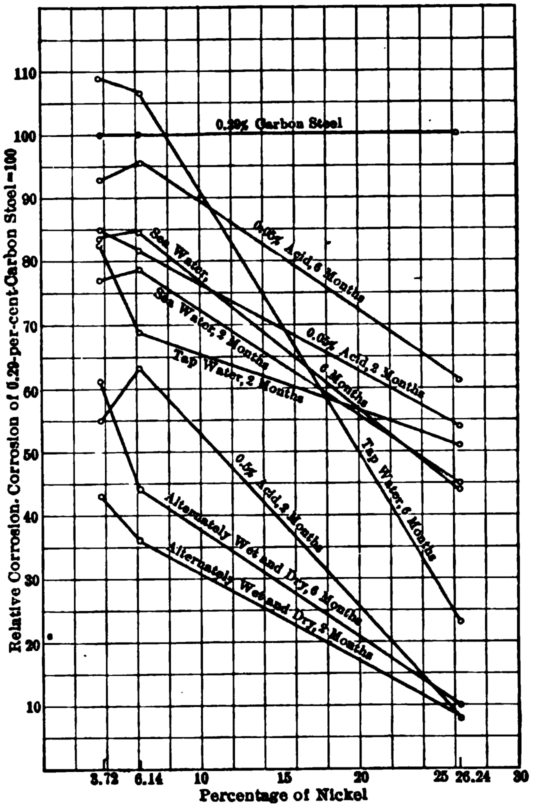

FIG. 294.—Relative Corrosion of Various Nickel Steels. (Friend, Bentley and West.)

(1) Low-nickel steels (3.7–6.1 per cent nickel) generally corrode considerably less than carbon steel under any condition of exposure, and high-nickel steels (26 per cent nickel) corrode very much less than carbon steel under the same conditions (10 to 60 per cent as much).

(2) The superiority of nickel steels over carbon steels with respect to resistance to corrosion is somewhat less marked after six months' exposure than it is after two months'.

(3) The superiority of nickel steels appears to be most marked when the exposure consists in allowing the steel to be alternately wet and dry. The advantage of the nickel steel is less marked on exposure to weak acids and to sea water or tap water, but is still considerable, and especially so in the case of the high-nickel steel.

Manufacture and Uses. Nickel steel is usually made by the open-hearth process, but may be made by the Bessemer or crucible process. Nickel is added in the form of metallic nickel, or ferro-nickel, charged with the rest of the stock.

Not counting armor-plate, where nickel is alloyed with chromium, nickel steel is most used for structural work in bridges, railroad rails (on curves particularly), steel castings, ordnance, engine forgings, shafting (especially marine shafting), frames and engine parts of automobiles, wire cables, axles for cars and automobiles, etc.

503. Manganese Steel. Manganese steel usually contains from 11 to 14 per cent manganese and from 0.8 to about 1.5 per cent carbon. Manganese steel was introduced by Sir Robert A. Hadfield in England in 1887–1888, and has ever since held a unique position among alloy steels. When cast in the ingot manganese steel is almost as brittle as glass, and is so hard that no carbon steel will cut it. Reheating to about 1000° C., followed by quenching in water, has the remarkable effect of rendering the material very much tougher and very much more ductile without materially altering its hardness. No other known metal or alloy combines in an equal degree extreme hardness and great ductility. No treatment will materially soften manganese steel when cold, and it must therefore be usually cast to as nearly its final form as possible and subsequently be finished by grinding. Manganese steel is very fluid when molten, and sound castings are produced. The shrinkage is excessive, however, (often more than $\frac{3}{8}$ inch per foot). The metal may be worked or forged with great difficulty through a short range of temperatures above a red heat. It is practically non-magnetic under all circumstances unless it has long been maintained at about 450° to 500° C. Its habit of elongation after the yield-point is passed in tension differs from that of carbon steel in that it does not neck down, but its elongation and contraction of area are quite uniformly distributed over the entire length of the specimen.

Structure and Constitution. The presence of manganese in the amount normally used in manganese steels has been shown to be responsible for the complete suppression of the allotropic changes which normally occur in the heating or cooling of carbon steels. Sir Robert Hadfield has recently shown * that the heating and the cooling curves of cast and forged manganese steels containing from about 10.9 to about 13.4 per cent manganese do not show the slightest retardations at any point between $-200°$ C., and $+1355°$ C. Manganese steel has no critical points, therefore, and the steel at atmospheric temperatures or any temperature above or below atmospheric temperatures must be a solid solution of γ-iron, manganese, and carbon. (One exception to the above statement must be made in view of the fact that Sir Robert Hadfield has been able to develop critical points in the neighborhood of about 750° C., by prolonged heating at about 500° C. The steel so treated became slightly magnetic.)

Professors J. O. Arnold and A. A. Reed † have produced strong evidence tending to show that the manganese exists in combination with a portion of the iron and carbon as the double carbide, $3Fe_3C, Mn_3C$.

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* "Heating and Cooling Curves of Manganese Steel," Jour. Iron and Steel Inst., Vol. 88, 1913, II, p. 191.

† Jour. Iron and Steel Inst., Vol. 81, 1910, I, p. 169.

In view of the fact that manganese steel possesses no critical points, it is impossible in the present state of our knowledge of the problem to make any explanation of what constitutes the nature of the extraordinary change of structure which accounts for the transformation upon quenching of an extremely brittle material into that condition in which possesses greater ductility than any other iron or steel.

(In a very recent study of this problem Mr. W. S. Potter * obtained heating and cooling curves of manganese steels, which had been initially very slowly frozen and slowly cooled, which he believed exhibited distinct points in the neighborhood of 850° C., and less distinct points at a number of other temperatures. It appears not unreasonable to believe, however, that the slight retardations observed may have been due to instrumental errors.)

Tensile Properties. The remarkable properties of manganese steel above alluded to are forcibly illustrated by the diagrams of Fig. 295, which exhibit the tensile properties of steels containing from 0.84 to 21.69 per cent manganese. Steels which have been tested as rolled, others which have been forged, but not otherwise treated, and still others which have been quenched in water from a white heat are included in the series of test results presented. These diagrams constitute a summary of the historically famous tests of manganese steels published by the discoverer of the valuable properties of this alloy steel, Sir Robert Hadfield himself. This particular set of data has not been selected on account of its historical value, however, but because it covers the ground more comprehensively than any more modern data found available.

The following facts appear to be established by Hadfield's tests:

(1) As the manganese content of steel is raised above 1 per cent the carbon content tends to increase, the proportionate increase of carbon with respect to manganese gradually becoming greater with higher manganese steels.

(2) The tensile strength of rolled manganese steel which has not been subjected to any heat treatment increases only very slightly with increase in manganese and, in fact, does not nearly equal the strength which might be expected to characterize a carbon steel of the same carbon content. Moreover, the increase of manganese rapidly reduces the ductility, and no rolled manganese steel containing more than about 2.5 per cent manganese shows more than about 5 per cent elongation in a gauged length of 8 inches.

(3) The tensile strength of manganese steel which has been forged,

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* "Manganese Steel, with Especial Reference to the Relation of Physical Properties to Micro-Structure and Critical Ranges," Bull. Inst. Min. Engrs., April, 1914, p. 601.

but not otherwise heat-treated, increases fairly rapidly with increase in manganese between 7 and 19 per cent, but is very low for the 7-per-cent-manganese steel and never equals that of an ordinary steel of the same carbon content. The ductility of these steels is of a very low order, although they may be forged with care. The elongation is never in excess of about 5 per cent.

(4) The tensile strength of steels containing in excess of 7 per cent manganese mounts rapidly with increase in manganese until a maximum of more than 140,000 pounds per square inch is reached with about 13 or 14 per cent manganese. With still higher manganese content the strength rapidly falls off again.

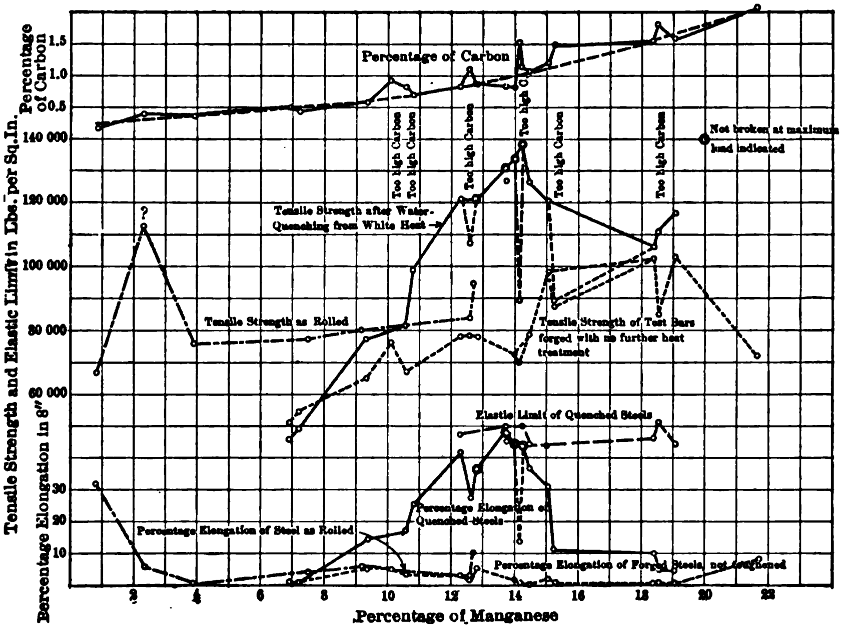

FIG. 295.—Tensile Properties of Manganese Steels. (Hadfield.)

More important than the tensile strength of the quenched steels, however, is the wonderful ductility developed. With only 7 per cent manganese the elongation is only about 1.5 per cent, but it rapidly increases with increase in manganese until a maximum elongation exceeding 50 per cent is reached when the manganese content is about 13 or 14 per cent. Further increases in manganese rapidly decrease ductility. The ductility and the tensile strength remain practically directly proportional for all percentages of manganese.

A comparison of the elongation of the quenched steel and the forged steel containing about 13 or 14 per cent manganese reveals the fact that the elongation has been raised by quenching from about 1 or 2 per cent to more than 50 per cent. At the same time the strength has been increased about 100 per cent, and the hardness has not been materially impaired. Some of these bars were bent cold, after testing, nearly 180°. In no case was there any sign of necking down, but the contraction of area and distribution of elongation were nearly uniform over the entire length of the reduced section of the test bars.

(5) The elastic limit, as determined by the " first permanent set " is very low in proportion to the tensile strength. For the steels containing from 13 to 15 per cent carbon the stress at the elastic limit amounted to only 35 to 40 per cent of the tensile strength, being about 50,000 pounds per square inch for the steels whose tensile strength exceeded 140,000 pounds per square inch.

(There are certain noticeable irregularities in these curves, certain test bars appearing to show abnormal properties. On account of the possibility that these anomalies might be explained by an abnormal carbon content, the amount of carbon in each steel has been indicated by the uppermost curve on the diagram, and what seems to be the normal carbon content is indicated by the dotted curve. A comparison between the carbon curve and the various strength and elongation curves now becomes very interesting. It would seem that practically every anomalous test result may be accounted for by an abnormal carbon content. Note particularly the steels containing respectively 10.11, 10.60, 12.60, 15.22, and 18.55 per cent carbon.)

Manufacture and Uses. Manganese steel is made by the open-hearth process whenever large masses are required. It may be made in the crucible, however. Manganese is added to the steel in the form of ferromanganese just before the completion of the process.

Large quantities of manganese steel are used as steel castings, particularly where great hardness and strength combined with great toughness are called for. It finds a special application in the construction of those parts of crushing and grinding machinery which are subjected to severe shock and abrasion. It is also used for curve rails, frogs, and crossings where hardness and freedom from brittleness constitute a great advantage, and to a limited extent for axles and treads of wheels of railway rolling stock. Its principal limitation in machine construction is the practical impossibility of machining it to final form by ordinary methods, on account of its excessive hardness.

504. Chrome Steel. Chrome steel usually contains from 1.5 to 2 or 2.5 per cent chromium together with from 0.7 to 1.5 or even 2.0

per cent carbon. Its value is due principally to its property of combining intense hardness after quenching with very high strength and extremely high elastic limit. It is therefore especially well able to withstand abrasion, cutting, or shock. The quenching treatment does not improve its ductility, as is the case with manganese steels, but on the other hand it is more ductile than a similarly treated carbon steel of the same carbon content.

Structure and Constitution. Thermal Critical Points. The characteristic structure of chrome steels containing less than about 5 or 6 per cent chromium does not differ materially from that of carbon steels similarly treated except for the presence of emulsified or finely granulated chromium carbide. With more than about 6 per cent chromium the structure of annealed steel " consists of chromiferous ferrite containing particles of double or triple (chromium) carbides, the carbide masses varying in size, some being very minute specks, and others of considerable dimensions." *

Arnold and Read found carbides in drastically annealed chrome steels corresponding to the following formulæ:

Per cent Carbon in Steel.	Per cent Chromium in Steel.	Formula which Approximately Agrees with Carbide Analysis.
0.64	0.65	$20Fe_3C,Cr_3C_2$
0.84	0.99	$12Fe_3C,Cr_3C_2$
0.835	4.97	$4Fe_3C,3Cr_3C_2,Cr_4C$
0.85	10.15	Fe_3C,Cr_3C_2,Cr_4C
0.85–0.88	15.02–23.7	$2Fe_3C,3Cr_4C$

From 80 to 99.7 per cent of the total amount of carbon in the steel was accounted for by the carbon found in the double and triple carbides.

Chrome steels possess distinct critical temperatures corresponding to those of ordinary carbon steels. Professor McWilliams and Mr. Barnes of the University of Sheffield have established the position of the critical points in heating and cooling 2 per cent chrome steels (with regard to carbon content) as indicated in the following table: †

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* Arnold and Read, " The Chemical and Mechanical Relation of Iron, Chromium and Carbon," Jour. Iron and Steel Inst., Vol. 83, 1911, I, p. 258.

† " Some Physical Properties of Two Per Cent Chromium Steels," Jour. Iron and Steel Inst., Vol. 81, 1910, I, p. 263.

CRITICAL TEMPERATURES OF 2 PER CENT CHROME STEEL

<table>
<tr><th>Per cent Carbon.</th><th>Ac_2. Deg. C.</th><th>Ac_1. Deg. C.</th><th>Ac_3. Deg. C.</th><th>Ar_3. Deg. C.</th><th>Ar_2. Deg. C.</th><th>Ar_1. Deg. C.</th></tr>
<tr><td>0.20</td><td>765</td><td>791</td><td>?822</td><td>785</td><td>765</td><td>732</td></tr>
<tr><td>0.25</td><td>759</td><td>789</td><td>?810</td><td colspan="2">758</td><td>731</td></tr>
<tr><td>0.32</td><td>753</td><td colspan="2">785</td><td colspan="2">748</td><td>733</td></tr>
<tr><td>0.50</td><td>759</td><td colspan="2">778</td><td colspan="3">721</td></tr>
<tr><td>0.65</td><td colspan="3">783</td><td colspan="3">718</td></tr>
<tr><td>0.85</td><td colspan="3">777</td><td colspan="3">714</td></tr>
</table>

Tensile Properties. The tensile properties of a series of steels containing from 0.62 to 32.46 per cent chromium are exhibited by the diagrams of Fig. 296. In order to avoid the disturbing factors incidental to the past history (heat treatment and mechanical working) of the steel from which the test specimens were cut, all of these specimens have been heated three hours at 850° C., prior to testing. The tests were made by M. Albert M. Portevin and represent a portion of the investigation of the special ternary steels above referred to.*

For the most part the iron-chromium carbon alloys represented by the diagram of Fig. 296 do not represent the particular alloys which are important as alloys steels. Only one or two facts illustrated by the diagram will therefore be noted, before considering certain special alloys which possess greater practical importance.

First. It should be noted that all of the steels containing between 1 and about 20 per cent of chromium show remarkably high tensile strengths, only one steel in this series showing less than 170,000 pounds per square inch tensile strength. (The fact should be borne in mind that these steels have not been quenched nor thoroughly annealed.)

Second. The elastic limit of most of these steels is remarkably high in proportion to the tensile strength.

Third. The ductility as indicated by the contraction of area is rather low for all of the steels except those containing in excess of about 20 per cent chromium.

Fourth. The tensile properties of all of the steels are closely dependent upon the carbon content, most of the anomalies in the various curves being directly attributable to an abnormal carbon content.

The steels whose tensile properties are indicated by the curves of Fig. 297 more nearly represent the chrome steels which are commercially used. The tests upon which these curves are based constitute a portion of the very detailed study of the physical properties of 2 per cent chrome

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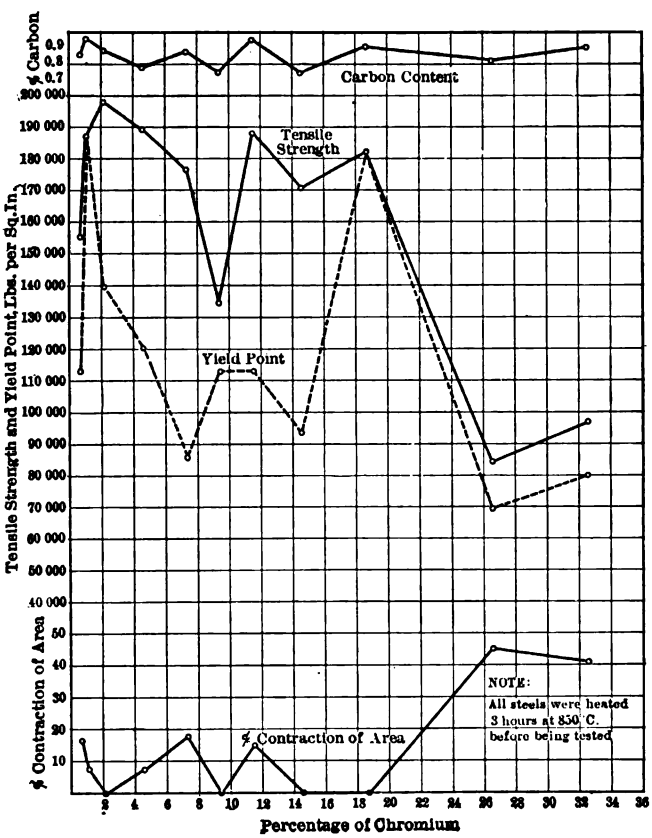
* See footnote, page 501.

steels made by Professor Andrew McWilliam and Mr. Ernest J. Barnes and referred to just above. The relation between tensile properties, carbon content, and heat treatment of 2 per cent chrome steels is exceptionally well shown by these tests. (It will be noted that this study of chrome steels parallels the study of nickel steels above quoted from another paper of the same investigators.)



NOTE: All steels were heated 3 hours at 850° C. before being tested.

FIG. 296.—Tensile Properties of Various Chrome Steels. (Portevin.)

The following general statements cover the most important facts established by this series of tests of 2 per cent chrome steels:

(1) The tensile properties of chrome steels, whether heat-treated in any manner or not, are dependent upon the carbon content to a very marked degree.

(2) In general the tensile strength and yield-point increase rapidly, and the ductility decreases, as the carbon content increases. The max-

imum beneficial effect of carbon would seem in most cases to be attained when the carbon content does not greatly exceed 0.7 or 0.8 per cent. (An exception to this statement must be made in the case of steels which have been neither hardened and tempered nor annealed.)

(3) The yield-point of 2 per cent chrome steels is remarkably close to the tensile strength in case the steel has been quenched and tempered.

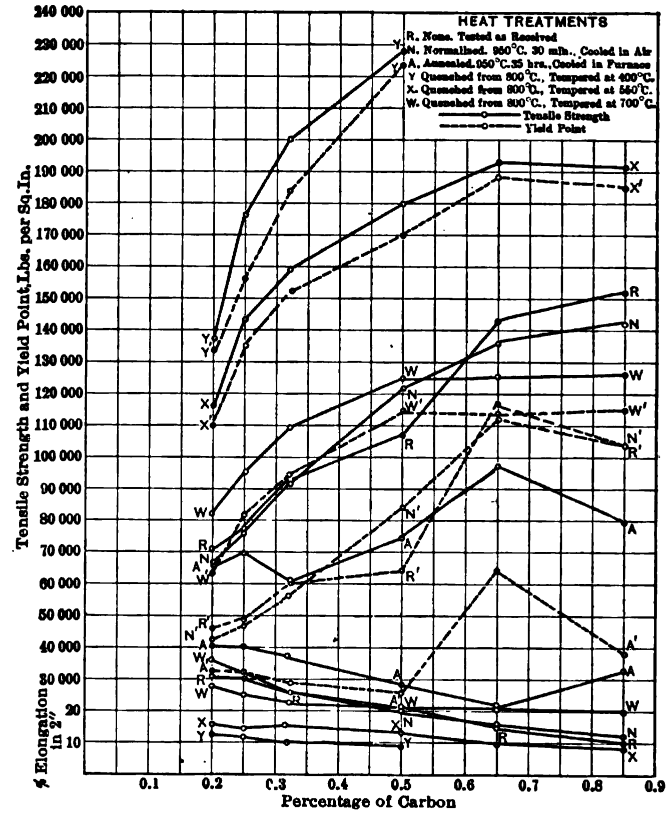


Fig. 297.—Relation of Tensile Properties of 2-per-cent-Chromium Steels to Carbon Content and Heat Treatment. (McWilliam and Barnes.)

With moderate tempering the yield-point may exceed 95 per cent of the tensile strength.

(4) The tensile properties of chrome steels which have not been heat-treated (hardened and tempered) do not excel those of ordinary steel of similar carbon content in any way except that they are slightly more ductile.

(5) The tensile strength is about doubled, the yield-point about tripled, and the ductility reduced about one-half, by quenching from 800° C., followed by tempering at 400° C. Tempering at higher heats reduces the strength and yield-point and increases the ductility in proportion to the tempering heat employed.

Quenching followed by moderate tempering raises the tensile strength of 0.2 per cent carbon steel from 67,000 to 137,000 pounds per square inch, and the yield-point from 42,000 to 134,000 pounds per square inch. When the carbon content is 0.5 per cent, this same treatment raises the tensile strength from 122,000 to 228,000 pounds per square inch, and the yield-point from 84,000 to 224,000 pounds per square inch.

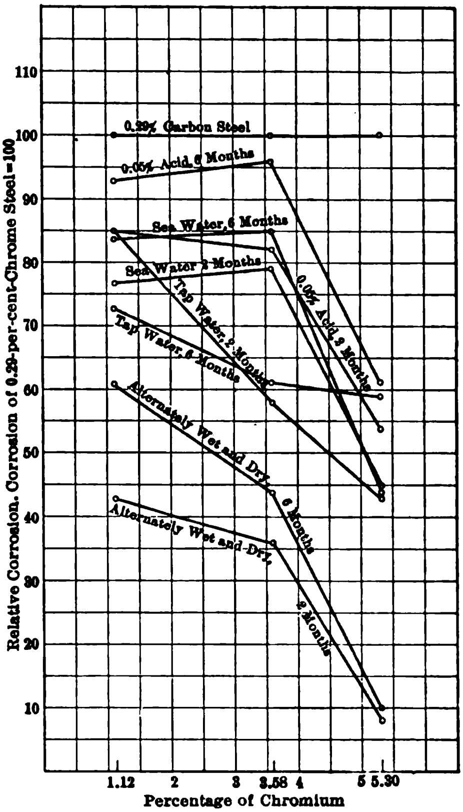


FIG. 298.—Relative Corrosion of Various Chrome Steels. (Friend, Bentley and West.)

(6) By drastic annealing at high heats, long prolonged, the tensile strength is very much reduced and the yield-point is lowered even more in proportion, while the ductility is very notably increased.

When it is recalled that the possession of this tremendous strength, and a yield-point unapproached by any other steel (except nickel-chromium steel), is combined with a hardness almost equal to that of manganese steel, the commercial value of this class of steel may be appreciated. It is rather lacking in ductility, but this is often unimportant in view of its extremely high elastic limit.

Corrodibility. The relative corrodibility of three chrome steels and a 0.29 per cent carbon steel in various media is exhibited by the curves of Fig. 298. This diagram is based upon data secured by Messrs. J. N. Friend, J. L. Bentley, and W. West in the experimental study of the problem above referred to in discussing the corrosion of nickel steels.* These corrosion tests constitute a portion of the same series of tests above quoted, and were made in the manner heretofore described.

The comparative corrodibility of these several chrome steels under the conditions of the tests may be expressed as follows:

(1) All chrome steels corrode less rapidly than ordinary carbon steel, but the advantage is far less marked in the case of the 1 per cent chrome steel than it is in the case of a 5.3 per cent chrome steel.

(2) The superiority of chrome steels over carbon steel with respect to resistance to corrosion is generally less marked after six months' exposure in any medium than it is after only two months.

(3) The superiority of chrome steels is most marked when the exposure consists in allowing the steel to be alternately wet and dry. The advantage conferred by the addition of the chromium is somewhat less marked on exposure to weak acids, sea water, or tap water, but is still considerable, and especially so in the case of 5.3 per cent chrome steel.

(Note that the findings of Messrs. Friend, Bentley, and West in the two series of corrosion tests—nickel and chrome steels—are almost identical in character.)

Manufacture and Uses. Chrome steel is made in the crucible or in the open-hearth furnace. Chromium is added in the form of ferrochrome, and since the latter oxidizes easily, the loss will be very heavy in the open hearth unless it is added just before the end of the process.

Chrome steel is used where a hard surface and shock resistance are desired. It is commonly used in the manufacture of projectiles and (in a quaternary alloy with nickel) armor plate. It is also used for a limited class of tools and dies, for gears and other parts of automobiles and machines generally, for the wearing parts of rock-crushing machinery, and for safes and vaults. In the latter application of chrome steel it is welded with alternate layers of wrought iron into a composite three- or five-ply plate. The chrome steel resists cutting by drills, while the wrought iron introduces an element of toughness so that it is better able to withstand concussion.

505. Tungsten Steel. Tungsten has long been recognized to be a most valuable alloy element for special steels. It is, however, most commonly used in conjunction with chromium or manganese in a quaternary alloy, instead of being used with carbon alone as a ternary alloy. The ternary alloys of iron, tungsten, and carbon possess a certain amount of commercial importance, however, and their properties will accordingly be briefly considered.

Tungsten steel usually contains from 3 to 10 per cent of tungsten

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* See footnote, page 511.

and from 0.2 to 1.0 or even 2.0 per cent carbon. The tensile properties of tungsten steel resemble those of high-carbon steel, the strength and especially the elastic limit being high, but the ductility low. After moderately rapid cooling from high temperatures, however, the tungsten steels exhibits remarkable hardness which is still retained upon heating to temperatures considerably above the ordinary tempering heats of carbon steels. It is this property of tungsten which makes it a valuable alloy for use (in conjunction with chromium or manganese), in making of the so-called " high-speed " tool steels.

The tungsten steel which contains about 4 or 5 per cent of tungsten and 0.5 to 0.7 per cent carbon possesses remarkable magnetic reluctance. It is a valuable material therefore for use in constructing permanent magnets, since when once magnetized, it will retain magnetism much longer than ordinary iron or steels.

Structure and Constitution. Thermal Critical Points. A general explanation of the structure and constitution of tungsten steels, including an explanation of the structural changes which take place when the steel is heated to a high degree and cooled with moderate rapidity, has never been satisfactorily made. Böhler,* H. LeChatelier,† Osmond,‡ H. C. H. Carpenter,§ Swinden,|| Edwards,¶ and others have, however, made important contributions to the study of the structure and thermal critical points of tungsten-carbon-iron alloys. All of these investigators found retardations, or critical points, in the cooling curves of tungsten steels, and, furthermore, it was shown by several of these gentlemen that a new critical point far below the ordinary critical range of temperatures appears when the steel has been cooled from temperatures in the neighborhood of 1200° C. This critical point has generally been understood to be the Ar_1 point of carbon steels, i.e., the temperature of formation of pearlite.

Böhler first proposed the theory that a sufficient amount of tungsten (or tungsten and chromium) is able to lower the lowest critical point below ordinary temperatures so that the change to the comparatively soft pearlite condition does not occur. Osmond went further and stated that this point of conversion to the pearlite state is lowered in propor-

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* " Wolfram und Rapid Stahl," 1903.

† " Revue de Métallurgie," 1904, pp. 334-347.

‡ " Contribution à la des Aciers rapides," 1904.

§ " The types of Structure and the Critical Ranges on Heating and Cooling of High-speed Tool Steels under Varying Thermal Treatments," Jour. Iron and Steel Inst., Vol. 67, 1905, I, p. 433.

|| " Carbon-Tungsten Steels," Jour. Iron and Steel Inst., Vol. 73, 1907, I, p. 291.

¶ Function of Chromium and Tungsten in High-speed Tool Steels," Jour. Iron and Steel Inst., Vol. 77, 1908, II, p. 104.

tion as the quantity of tungsten, chromium, etc., is raised above the eutectoid composition. Carpenter found, however, that the low critical point occurs at about 400° C., in all cases when tungsten, molybdenum, tungsten-chromium, or molybdenum-chromium high-speed steels are cooled from 1200° or 1250° C. Later, Edwards showed that all the alloys containing more than 6.0 per cent of tungsten and 3.0 per cent of chromium show a low critical point at about 380° C., when cooled from 1200° C., but exhibit no critical point below 900° C., when cooled from 1320° C. (almost the melting temperature). Edwards also observed that if the effect of the tungsten is simply a depression of the Ar_1 carbon change point it is implied " that the low point is still the carbide of iron change, and a steel slowly cooled below this temperature ought to revert to the annealed condition. If so, on again heating to much below the lowering temperature, say 900° C., and immediately cooling, the carbon change point (Ar_1) ought to appear at the normal temperature, since an initial temperature of 900° C. has no effect on this point . . . This is not the case. Thus after cooling below the low point several times, it is necessary to soak this sample for a half hour before the Ar_1 point appears at the normal temperatures, and even after this treatment the low point is still visible."

Accordingly, Mr. Edwards expressed the opinion " that the low point is not Ar_1 lowered by tungsten, but that a carbide of tungsten is slowly formed at about 1200° C., which has a critical temperature quite independent of Ar_1."

The influence of the chromium in tungsten-chromium steels was shown by both Carpenter and Edwards not to be in the direction of lowering the Ar_1 point, but actually the reverse. Edwards therefore concluded that, since the tungsten-chromium steels cooled from 1320° C., did not show any low point, that " the carbide of chromium first formed at 1200° C. combines with the chromium at higher temperatures to form the double carbide. This double carbide is held in solution on cooling, even slow cooling, but on heating it is deposited from solution at 670° to 730° C., and is slowly decomposed at slightly higher temperatures, first into carbide of tungsten, and on soaking, iron carbide is again formed. . . . Thus the double carbide is held in solution even when slowly cooled in air. To prevent the carbide of tungsten being deposited, the steels must be quenched in an air blast; whilst the carbide of iron is only kept in solution by quenching in water."

Tensile Properties. The tensile properties of two series of steels containing from 0.4 to 27.05 per cent tungsten, together with about 0.2 per cent carbon, and about 0.8 per cent carbon, respectively, are exhibited by the diagrams of Fig. 299. This diagram is based upon a series of tests made by Portevin.* It will be noted that for both series of steels the tensile strength and elastic limit increase with increase in tungsten until a maximum strength is reached with 10 per cent tungsten, and 12 per cent tungsten, in the respective cases of the high- and low-carbon steels. The ductility is also reduced with increase in tungsten. (These steels have been heated three hours at 850° C., prior to testing.)

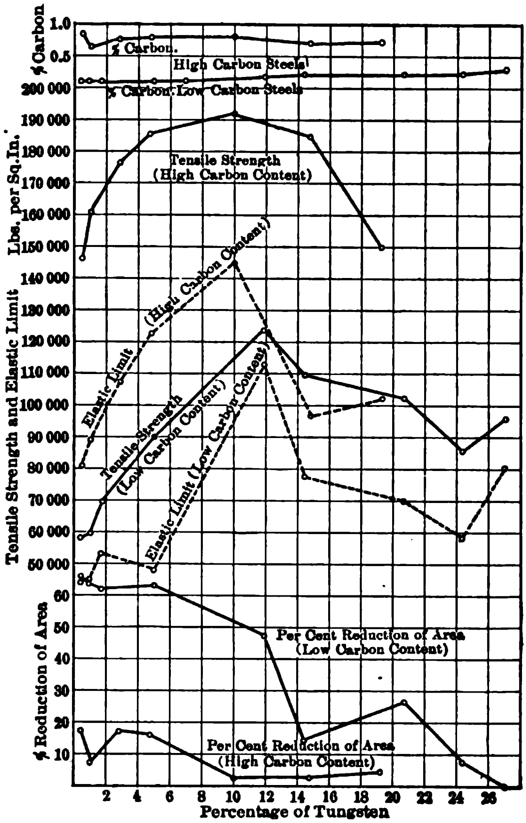

FIG. 299.—Tensile Properties of Tungsten Steels. (Portevin.)

The marked difference in the properties of a high- and a low-carbon tungsten steel is shown by a comparison of the curves of Fig. 299. The important relation of the carbon content to the properties of tungsten steel is shown to better advantage, however, by the tests of Mr. Thomas Swinden,† which are summarized by the curves of Fig. 300. The steels comprising this series all contained approximately 3 per cent tungsten, while the carbon content varied from 0.144 to 1.07 per cent. They were normalized by heating to 950° C., maintaining this temperature for fifteen minutes, and cooling freely in air.

It is very evident that increase in carbon is beneficial to the strength and elastic limit of this 3-per-cent-tungsten steel, until a limiting percentage of about 0.9 per cent is reached. The ductility naturally decreases with increase in strength. (The maximum beneficial percentage of carbon may be higher than 0.9 when the tungsten content exceeds 3 per cent.)

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* "Contributions to the Study of the Special Ternary Steels," p. 260.

† "Carbon-Tungsten Steels," p. 294.

The upper curves of Fig. 300 indicate that increase of carbon content beyond about 0.3 per cent is detrimental to the ability of the steel to withstand cold bending or alternating stresses. With respect to the alternating stress tests it may be added that the showing of these steels is not equal to that of ordinary boiler-plate steels, which are expected to stand about 350 reversals of bending stress in the Arnold machine.

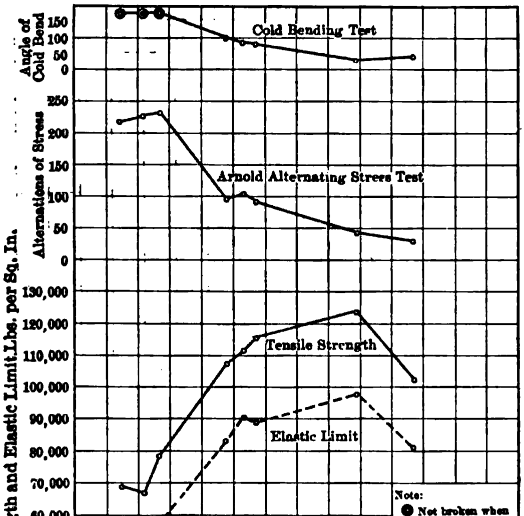

FIG. 300.—Relation of Tensile Properties of 3-per-cent-Tungsten Steels to Carbon Content. (Swinden.)

Manufacture and Uses. Tungsten steel is made almost exclusively by the crucible process, the tungsten being added in the form of ferro-tungsten, as wolframite (WO_4), or less commonly, as metallic tungsten.

Tungsten steel is used for few purposes other than for machine tools. These must be forged roughly to form and finished by grinding. The great advantage of this steel over ordinary high-carbon tool steel is its ability to hold its hardness at high temperatures, thus making it possible to run machines at high speed with heavy cuts. It is excelled in this respect, however, by the special steels classed as "high-speed" tool steels, which contain chromium or manganese in addition to tungsten. The uses of tungsten steel as a magnetic steel has been mentioned above.

506. Molybdenum Steel. The action of molybdenum in steels is generally accepted to be exactly similar in character to that of tungsten in so far as the influence of the alloy upon critical temperatures, hardening power, physical properties, etc., are concerned, but the effect of molybdenum differs in magnitude from that of tungsten, 1 per cent of molybdenum being apparently equivalent to 2 or 3 per cent of tungsten.

Most molybdenum steels are really quaternary alloys, since chromium or magnesium is usually present in notable amounts. The best molybdenum ternary alloy steels contain from 1 to 2 or 3 per cent molybdenum and not more than 2 per cent carbon. The general physical characteristics of molybdenum steels are identical with those of tungsten steel.

Structure and Constitution. Thermal Critical Points. Mr. Thomas Swinden concluded as a result of an extensive study of the constitution of carbon molybdenum steels * that " molybdenum does not exist as double carbide, and is not in solid solution in the iron, but is probably dispersed in the ferrite in a manner suggesting the existence of a solid colloidal solution of an iron-molybdenum compound in iron." This condition is of course in opposition to Edward's theory respecting tungsten steels above quoted.

Swinden shows by a series of cooling curves that is the initial temperature has not exceeded a certain definite minimum the steel behaves in every way like plain carbon steel. If the initial temperature has exceeded a certain minimum " lowering temperature," however, a new low critical point appears far below the normal position of Ar_1, just as has been shown to be the case with tungsten steels. The minimum lowering temperature is somewhat lower in molybdenum steels than in tungsten steels, and when the molybdenum content is high (8 per cent) appears to be as low if not lower, than the *Ac* point. The temperature at which the maximum lowering effect is derived increases with increase in carbon and with increase in molybdenum. Thus a steel containing about 1.2 per cent carbon and about 1.0 per cent molybdenum showed the lowest critical point obtainable upon cooling from 1000° C., while a steel of about the same carbon content, but having 4.0 per cent molybdenum, was similarly affected only by a temperature of 1200° C.

The position of the low point is absolutely independent of the carbon content, but becomes lower as the molybdenum content increases. With 1.0 molybdenum its position was found to be about 560° C., but with 4 per cent molybdenum it is probably below 440° C.

The actual explanation of the behavior of molybdenum steels upon cooling with moderate rapidity from the temperature above called the " lowering temperature " is still a subject of much controversy, just as is the case with tungsten steels and the quaternary steels which exhibit similar properties. The fact of the greatest practical importance, however, is that such heat treatment does cause some structural change

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* " Carnegie Scholarship Memoirs," Vol. 5, 1913, p. 100.

the result of which is the acquirement of intense hardness, which is not lost on reheating until temperatures considerably above that temperature at which ordinary steel assumes the soft pearlite state is reached.

Tensile Properties. The tensile properties of a series of molybdenum steels containing from 1.0 to 8.0 per cent molybdenum and 0.2 to 1.2 per cent carbon are exhibited by the curves of Fig. 301. These tests constitute a portion of Swinden's study of molybdenum steels above referred to.

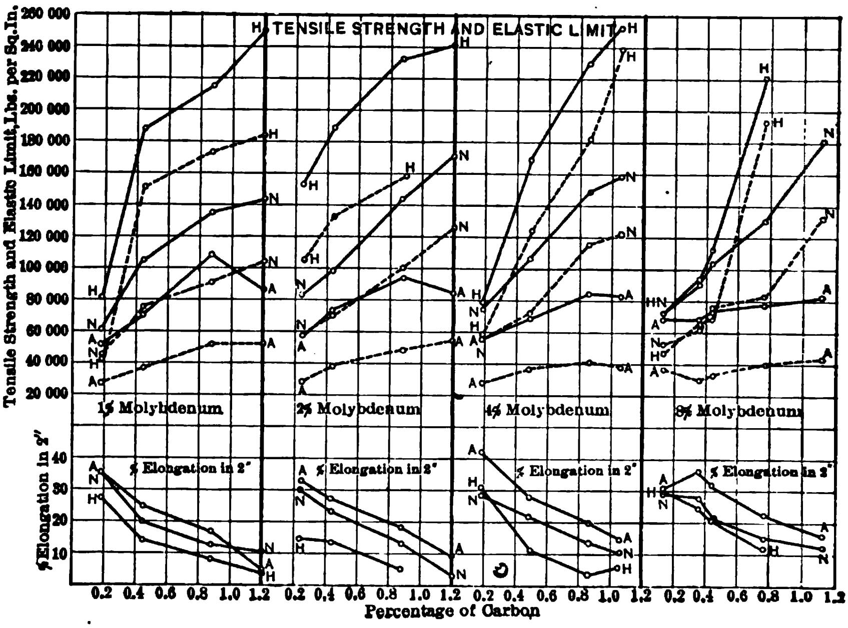

FIG. 301.—Tensile Properties of Molybdenum Steels. (Swinden.)

Tensile Strength ——————o——————

Elastic Limit ··················o··················

N. Normalized, 15 min. at 900° C., Air cooled.

A. Annealed, 5 hrs., at 950° C., Cooled in Furnace.

H. Hardened and Tempered, Quenched at 950–800° C. in Oil.

The diagram is self explanatory and it will not be necessary to discuss it beyond the point of simply calling attention to the fact that with a given molybdenum content the strength and elastic limit are increased and the ductility decreased rapidly as the carbon content is raised. Quenching from a temperature of from 800° to 900° C. is very beneficial to tensile properties with the exception of ductility.

Ductility as Indicated by Cold Bending. The results of cold-bending tests of the steels of the series used for tensile tests are shown by the curves of Fig. 302. Contrary to what might have been expected increase in molybdenum content seems to improve the ductility of steels containing a given amount of carbon (providing they have not been quenched). This fact is shown by both the elongation in tensile tests and the degree of bending cold.

Alternating Stress Resistance. Fig. 302 shows that molybdenum steels do not rank exceptionally well when compared with carbon steels on the basis of their relative performance under alternating stress. The steels containing from 2 to 4 per cent molybdenum seem to rank highest, but the carbon content is a much more potent factor than the molybdenum content unless the steels have been quenched.

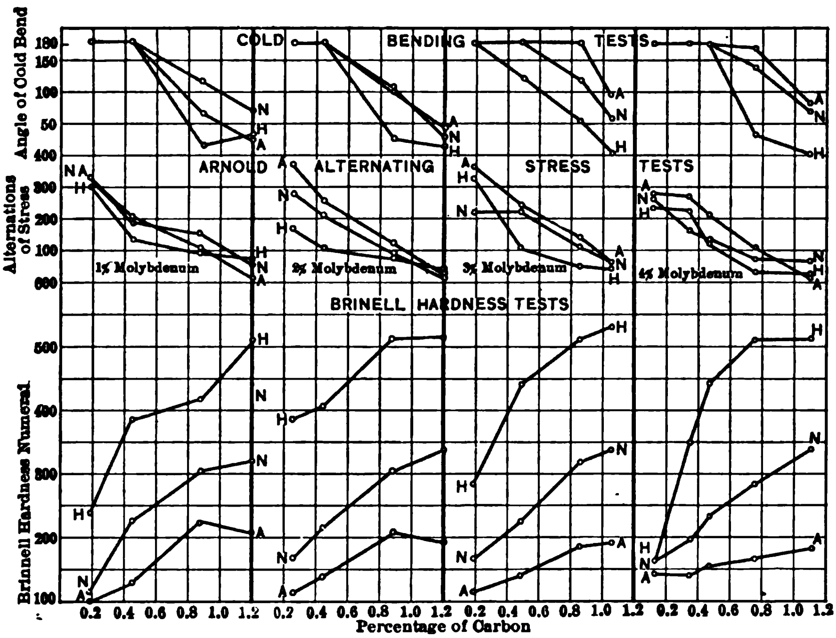

FIG. 302.—Cold Bending, Alternating Stress, and Brinell Hardness of Molybdenum Steels. (Swinden.)

Brinell Hardness. The Brinell hardness, as is shown by Fig. 302, increases rapidly with the carbon content, and seems to be only slightly affected by the molybdenum content when the steels have not been quenched at temperatures above the minimum lowering temperature. (No data have been found available to show the hardness of these steels after cooling from the lowering temperature.)

Manufacture and Uses. Molybdenum steels are made in the crucible in the same manner as tungsten steels, and have practically the same uses. The manufacture of these steels in the United States is controlled by patents and the production has been limited by this circumstance.

507. Silicon Steel. Silicon steels resemble nickel steels in their general properties, but have not been used as extensively as a material of engineering construction. When 1 or 2 per cent of silicon is combined with from 0.1 to 0.4 per cent of carbon the resultant steel is one which may be classed as a high-strength structural steel resembling nickel structural steel. It is chiefly valuable because its elastic limit is very high, compared with that of an ordinary steel of equal carbon content. It is rather hard, however, and gives some difficulty in rolling.

The most valuable silicon steel is the one which is made particularly for use in electrical machinery and which was developed by Hadfield and patented in this country in 1907. Hadfield's silicon steel contains about 3 per cent of silicon (2.75 per cent recommended) and the smallest possible amounts of carbon, manganese, and other impurities. This steel acquires its remarkable magnetic properties (very high permeability and low core loss) only after a special heat treatment. It is heated to between 900° and 1100° C. (1070° C. recommended), cooled quickly to atmospheric temperatures, reheated to between 700° and 850° C. (750° C. recommended), and cooled very slowly. Sometimes it is again heated and cooled very slowly from about 800° C. The magnetic properties of this class of steel have been discussed above. (See Art. 497 and Fig. 277.)

Tensile Properties. The tensile properties of a series of very low-carbon silicon steels are exhibited by Fig. 303. These curves are based upon tests made by Mr. Thomas Baker in 1913.* These steels do not excel ordinary medium high-carbon steels in tensile strength nor ductility, but do show a very high elastic limit. In the presence of so small an amount of carbon (0.04 per cent), the addition of silicon seems to be beneficial to strength only in amounts not exceeding about 5 per cent, and all of these steels acquire great brittleness if about 2.0 per cent silicon is exceeded.

Similar tests made by Hadfield at an earlier date † with steels containing about the same range of silicon content, but having from 0.14 to 0.26 per cent carbon (Fig. 303), exhibit about the same properties as the very low-carbon steels used by Baker, except that the strength and elastic limit is slightly higher. Hadfield found forging of his steels impossible when the silicon content exceeded 5.5 per cent.

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* "The Influence of Silicon on Iron," Jour. Iron and Steel Inst., Vol. 64, 1913, II, p. 312.

† Jour. Iron and Steel Inst., 1889, II, p. 222.

Manufacture and Uses. Silicon steel may be made in the crucible, but is more often made in the open hearth. The alloy element is added in the form of ferro-silicon. A small amount of silicon steel has been used as a hard, high-strength, structural steel for purposes similar to those above noted in discussing nickel steel. The principal commercial application of this alloy, however, is as thin sheet steel for the construction of the cores, pole pieces, etc., of electrical machinery.

508. Vanadium Steels. Vanadium is, with the single exception of carbon, the most powerful element for alloying with iron yet discovered. Only 0.1 to 0.15 per cent of vanadium raises the tensile strength and elastic limit of low- or medium-carbon steel 50 per cent or more without any sacrifice of ductility. With high-carbon content (about 0.8 per cent carbon), and about 0.2 per cent vanadium, the tensile strength is about equal to that of an ordinary steel of corresponding carbon content, but the elastic limit is very much higher and the steel is much more ductile than a similar carbon steel.

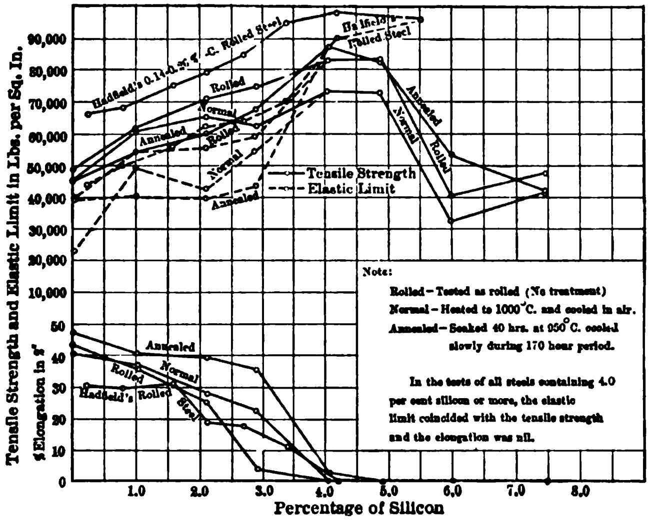


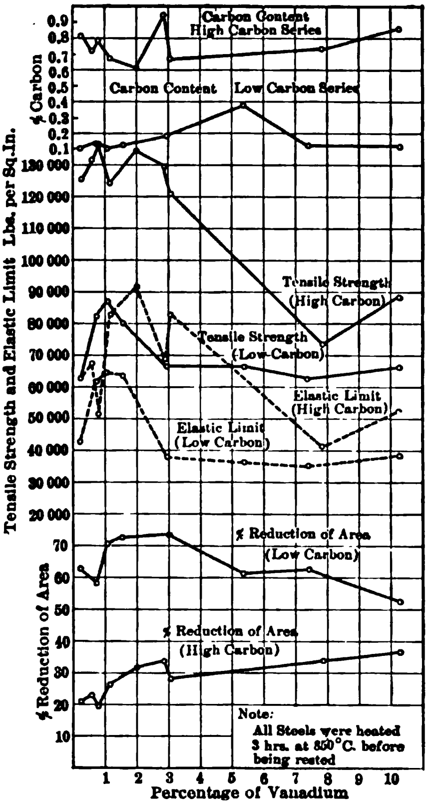
FIG. 303.—Tensile Properties of Steels Containing 0.04 per cent Carbon. (Baker.)

Little more than 0.2 per cent vanadium seems to be advantageous in any steel, and amounts exceeding about 0.3 per cent are very detrimental to strength.

Vanadium steels may be forged or rolled with only minor special precautions; they respond readily to heat treatments; are enormously strong when hardened by quenching and moderately tempered; and are very tough, and stand impact, vibration, or reversal of stress very well.

Vanadium has an important quieting influence upon molten steel when cast in the ingot, and therefore promotes soundness by preventing the occlusion of gases.

The use of vanadium in steels designed for a great variety of purposes is becoming more common every year, and, in addition to the ternary alloys of vanadium carbon and iron, vanadium is used in a variety of quaternary alloy steels in which chromium, nickel, etc., are also present.



Note: All Steels were heated 3 hrs. at 850°C. before being rested

FIG. 304.—Tensile Properties of Various Vanadium Steels. (Portevin.)

Structure and Constitution. The structure and constitution of vanadium steels, either normal or heat-treated, do not differ from those of corresponding carbon steels. The vanadium appears to exist for the most part as a carbide, but a small amount is usually also present in the free ferrite. The thermal critical points seem not to be markedly affected by the small amount of vanadium used. The beneficial effect of vanadium upon the strength and ductility of steels cannot be definitely explained, but is probably due partly to its beneficial effect upon the behavior of the molten metal above noted. The formation of carbide and the presence of vanadium in the ferrite may also constitute advantageous factors.

Tensile Properties. The tensile properties of two series of steels containing about 0.2 per cent, and about 0.8 per cent carbon, respectively, are shown by Fig. 304. The tests represented by this diagram constitute a portion of Portevin's study of ternary alloys referred to above.

The beneficial effect of from 0.1 to 0.3 per cent vanadium upon tensile strength and, more particularly, the elastic limit, is plainly shown by these tests. The remarkable ductility of these steels, as indicated by the percentage of reduction of area, is also worthy of special note.

The important influence of carbon content and heat treatment upon the tensile properties of a series of 0.2-per-cent-vanadium steels is shown by Fig. 305. This diagram is based upon another of the wonderfully painstaking researches of Messrs. McWilliam and Barnes.*

This diagram shows that the tensile strength and yield-point of 0.2-per-cent-vanadium steels increase rapidly with increase in carbon until a steel containing about 1.0 per cent carbon is reached. Beyond this point increase in carbon content is not beneficial, and may be the reverse. The ductility decreases only very slowly with increase in carbon, and is still considerable when the 1 per cent carbon steel is reached.

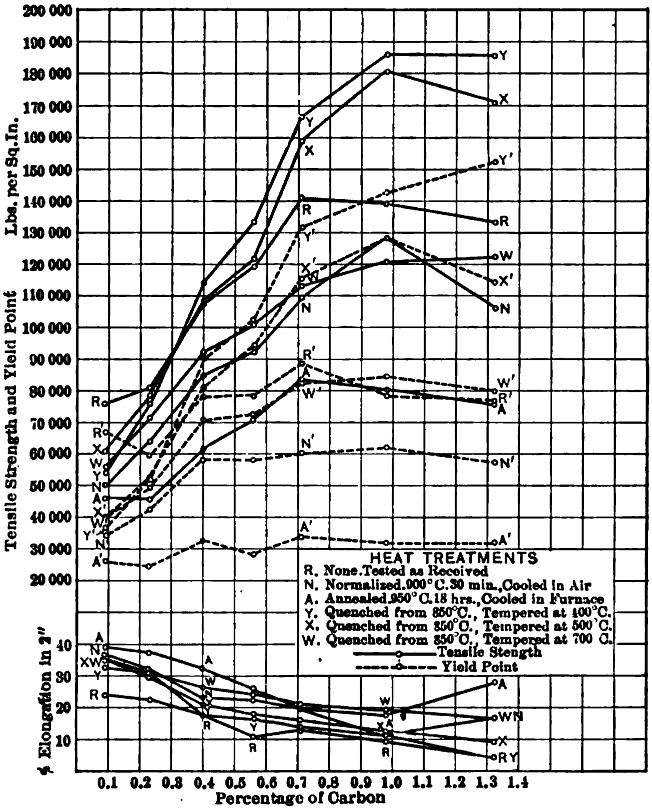


Fig. 305.—Relation of Tensile Properties of 0.2-per-cent-Vanadium Steels to Carbon Content and Heat Treatment. (McWilliam and Barnes.)

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* "Influence of 0.2 Per Cent Vanadium on Steels of Varying Carbon Content," Jour. Iron and Steel Inst., Vol. 83, 1911, I, p. 294.

The diagram also shows that vanadium steels are very responsive to heat treatments, the effect of the hardening treatment followed by moderate tempering being especially remarkable because of the extent to which the yield-point and, less notably, the tensile strength is raised.

Manufacture and Uses. Vanadium steels were originally made in the crucible, but are now commonly made in large masses in the open hearth. The vanadium is added in the form of ferro-vanadium, introduced after the recarburizer has been added when the conditions of the process are reducing, rather than oxidizing, in order to avoid loss by oxidation.

Vanadium steel is used to a considerable extent for castings and forgings for machines, automobiles, and railway rolling stock. It is also used for axles, springs, shafting, and gears, and a structural grade of vanadium steel has recently been introduced, the material being rolled to the ordinary structural shapes, and used in the construction of long-span bridges and other structures subjected to severe conditions of service.

QUATERNARY ALLOYS

509. The Quaternary Alloys. Many of the quaternary alloy steels are no less important commercially than the ternary alloys discussed in some detail above. Unfortunately, however, the quaternary alloys have not been as systematically studied as have most of the ternary alloys, and no effort will therefore be made to consider separately the properties of each one in detail.

The most comprehensive study of quaternary alloys available is that made by Dr. Léon Guillet in 1906,* and all of the data quoted hereinafter is derived from Dr. Guillet's valuable paper. On account of the fact that the science of metallography has developed to so great an extent since the date of this study, the section of the paper devoted to micrography will not be considered. The study of the mechanical properties of quaternary alloys will be extensively quoted, however.

On account of the number of variable factors involved, the properties of the quaternary alloys cannot conveniently be represented by curves. For this reason the following series of tables are inserted. The tables are intended to be self-explanatory, and it is therefore considered unnecessary to discuss the results of the very large number of tests which are summarized.

The author has omitted a certain portion of the tests which seemed

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* "Quaternary Steels," Carnegie Scholarship Memoirs, Jour. Iron and Steel Inst., Vol. 70, 1906, II, pp. 1-142.

least significant, has rearranged the data for convenience in reference, and has converted the strength values from metric to English units.

The tensile specimens used were round bars, 13.8 millimeters in diameter, and 100 millimeters between gauge points (½ inch by 4 inches, nearly). All specimens marked "normal" had been normalized by heating at 900° C., followed by slow cooling. The "quenched" specimens were quenched in water from 850° C., except certain of the tungsten-chromium steels whose special treatment is noted.

PROPERTIES OF QUATERNARY ALLOYS

NICKEL-TUNGSTEN STEELS

Approx. Composition.			Tensile Strength, Lbs. per Sq. In.		Elas. Limit, Lbs. per Sq. In.	Elongation, per cent in 4″	Brinell Hardness.	
C.	Ni.	W.	Normal.	Quenched.	Normal.	Normal.	Normal.	Quenched
0.2	6.0	0.3	78,100	227,400	63,700	21.0	146	387
	5.0	0.3	96,700	226,000	78,800	17.0	179	418
	6.0	0.7	90,900	....	81,000	16.0	192	444
		2.0	105,300	220,500	81,000	14.0	207	387
		6.0	125,400	177,700	90,700	16.0	226	302
0.4	3.0	0.3	93,500	....	66,800	13.5	196	321
	4.0	0.7	88,400	....	64,700	15.5	174	555
	4.0	2.0	105,300	....	89,500	13.0	207	477
	4.0	5.0	108,800	....	85,700	14.0	217	495

NICKEL-VANADIUM STEELS

Approx. Composition.			Tensile Strength, Lbs. per Sq. In.		Elas. Limit, Lbs. per Sq. In.	Elongation, per cent in 4″	Brinell Hardness.	
C.	Ni.	Va.	Normal.	Quenched.	Normal.	Normal.	Normal.	Quenched
0.2	6.0	0.1	86,700	218,900	69,700	24.5	166	302
		0.3	108,100	223,200	81,800	18.0	192	293
		0.5	103,100	204,700	82,700	19.0	235	321
		0.7	119,400	226,700	93,100	15.5	235	321
0.4	3.5	0.1	96,400	....	69,700	21.0	179	402
	3.0	0.3	98,300	....	73,900	20.0	196	460
	3.5	0.5	103,800	183,500	81,000	19.0	183	460
	3.0	0.7	109,500	....	79,900	16.0	166	375

NICKEL-MANGANESE STEELS

Approx. Composition.			Tensile Strength, Lbs. per Sq. In.		Elas. Limit, Lbs. per Sq. In.	Elongation, per cent in 4"	Brinell Hardness.	
C.	Ni.	Mn.	Normal.	Quenched.	Normal.	Normal.	Normal.	Quenched
0.15	2.0	5.0	201,300	....	140,800	6.0	311	340
		7.0	....	218,700	....	......	364	444
		15.0	99,800	....	41,700	7.0	187	187
	12.0	5.0	152,800	122,800	58,600	15.5	212	223
		7.0	87,800	89,300	50,200	36.5	146	131
		15.0	93,400	....	65,400	35.5	170	118
	30.0	5.0	100,400	92,000	38,400	30.0	149	126
		7.0	102,700	83,600	38,400	22.0	124	107
0.75	2.0	5.0	....	107,000	....	......	277	255
		7.0	105,000	91,400	62,000	3.0	235	223
		15.0	114,200	116,000	70,500	18.0	212	183
	12.0	5.0	143,400	....	59,200	11.5	174	153
	30.0	5.0	132,600	104,800	36,300	32.0	174	153
		7.0	123,600	102,700	38,400	30.0	196	137

CHROMIUM-MANGANESE STEELS

Approx. Composition.			Tensile Strength, Lbs. per Sq. In.		Elas. Limit, Lbs. per Sq. In.	Elongation, per cent in 4"	Brinell Hardness.	
C.	Mn.	Cr.	Normal.	Quenched.	Normal.	Normal.	Normal.	Quenched
0.2	3.0	3.0	136,300	168,600	89,800	5.0	293	364
		5.0	174,200	154,300	174,200	0.0	444	418
	10.0	3.0	126,000	155,400	68,900	4.0	248	444
		5.0	108,300	117,200	33,400	29.0	196	234
	15.0	3.0	125,700	122,800	40,100	19.5	114	105
0.8	2.0	3.0	136,000	153,300	119,800	8.0	364	477
		5.0	118,700	138,700	92,500	10.0	302	418
	12.0	3.0	101,600	97,400	50,100	25.0	183	159
		5.0	122,600	105,700	58,700	14.0	217	179

NICKEL-CHROMIUM STEELS

Approx. Composition.			Tensile Strength, Lbs. per Sq. In.		Elas. Limit, Lbs. per Sq. In.	Elongation, per cent in 4"	Brinell Hardness.	
C.	Ni.	Cr.	Normal.	Quenched.	Normal.	Normal.	Normal.	Quenched
0.20	5.0	3.0	143,800	203,400	117,800	10.0	248	444
		10.0	162,100	241,800	98,100	8.0	402	418
	12.0	3.0	236,000	276,700	236,000	6.0	430	475
		10.0	174,800	....	93,800	14.0	277	332
		20.0	130,800	129,300	110,600	20.0	225	217
	30.0	3.0	98,100	91,700	69,700	26.0	121	137
		10.0	128,700	125,600	97,900	10.0	143	196
0.80	5.0	3.0	21,750	....	21,750	1.5	255	402
		10.0	204,700	....	20,480	2.0	555	512
	12.0	3.0	174,100	209,000	113,100	29.5	311	302
		10.0	118,000	130,800	56,800	33.5	286	196
0.30	2.5	0.5	77,800	....	60,600	24.4	137	418
		1.0	78,200	176,000	57,200	23.0	146	430
		2.0	98,300	190,500	65,100	20.0	166	430
		3.0	197,600	230,300	197,600	0.0	275	444
		5.0	230,400	266,000	191,900	4.5	248	444
0.20	6.0	0.5	108,100	203,400	64,700	18.0	183	277
		1.0	170,500	228,700	146,500	12.0	286	460
		2.0	223,300	201,900	174,800	7.0	375	418
		5.0	238,800	187,700	193,300	6.0	402	387
		6.0	155,000	214,600	155,000	0.0	460	402

MANGANESE-SILICON STEELS

Approx. Composition.			Tensile Strength Lbs. per Sq. In.		Elas. Limit. Lbs. per Sq. In.	Elongation, per cent in 4'	Brinell Hardness.	
C.	Mn.	Si.	Normal.	Quenched.	Normal.	Normal.	Normal.	Quenched
0.2	2.0	0.5	70,600	93,100	40,600	17.5	107	234
		0.7	79,300	151,900	57,900	15.5	107	248
		1.5	85,600	164,200	65,900	14.0	153	269
	15.0	1.0	112,500	100,100	33,200	10.0	212	196
		2.0	134,300	153,100	70,600	5.0	248	300
0.5	0.5	1.0	109,000	....	71,500	12.0	248	
		2.0	118,300	....	77,100	10.0	293	
	12.0	0.5	103,000	....	68,600	19.0	196	
		1.0	107,700	....	65,900	15.0	202	
		2.0	103,400	....	69,800	10.0	202	

NICKEL-SILICON STEELS

Approx. Composition.			Tensile Strength, Lbs. per Sq. In.		Elas. Limit, Lbs. per Sq. In.	Elongation, per cent in 4"	Brinell Hardness.	
C.	Ni.	Si.	Normal.	Quenched.	Normal.	Normal.	Normal.	Quenched
0.2	2.0	0.5	72,600	239,500	51,000	20.5	124	418
		1.0	84,700	196,300	50,700	16.0	126	351
		1.5	104,500	183,500	73,100	19.0	179	351
		2.0	114,300	179,000	74,200	13.0	163	430
		5.0	137,900	162,800	108,700	16.0	235	277
	6.0	0.5	85,000	219,000	69,700	23.5	170	340
		0.8	103,800	209,000	59,700	23.0	170	321
		1.0	110,900	....	78,200	19.0	163	304
		2.0	166,300	....	125,200	11.0	248	444
		5.0	96,700	142,900	96,700	0.0	286	556
	12.0	0.5	200,500	196,300	200,500	1.0	351	387
		1.0	204,300	165,300	204,300	0.0	375	444
		2.0	241,500	288,500	241,500	9.0	375	375
		3.0	167,300	230,700	167,300	0.0	402	460
		5.0	202,600	153,600	202,600	2.0	430	418
		7.0	225,900	173,000	225,900	0.0	460	387
	30.0	2.0	88,000	85,400	34,700	36.0	143	140
		5.0	94,100	94,100	30,700	40.0	159	143
0.4	3.0	0.5	93,200	....	64,700	20.0	170	477
		1.0	124,400	....	80,200	12.5	174	
		1.5	112,900	....	87,000	6.5	202	477
		2.0	138,700	....	101,700	14.0	228	
		3.0	152,200	....	120,800	2.5	262	555
		7.0	....	....	....	......	286	
0.8	2.0	2.0	180,000	....	100,200	8.0	293	495
		5.0	119,100	....	98,100	9.5	351	512
	12.0	2.0	147,100	....	147,100	0.0	153	364
	15.0	1.0	118,000	....	118,000	0.0	143	332
		2.0	120,800	....	120,800	0.0	179	364
		3.0	240,300	....	240,300	0.0	196	364
	20.0	1.0	133,700	98,100	32,700	33.0	143	116
		3.0	170,600	103,800	38,400	27.0	134	166

TUNGSTEN-CHROMIUM STEELS

(Quenched steels heated to 850° C.)

Approx. Composition.			Tensile Strength Lbs. per Sq. In.		Elas. Limit. Lbs. per Sq. In.	Elongation, per cent in 4"	Brinell Hardness.	
C.	Cr.	W.	Normal.	Quenched.	Normal.	Normal.	Normal.	Quenched
0.2	2.0	2.0	77,800	140,800	39,700	17.0	126	261
		15.0	96,100	92,100	36,100	10.0	153	170
	3.0	13.0	91,000	....	47,800	15.6	166	163
	10.0	2.0	243,700	186,800	210,000	4.5	477	375
		15.0	122,800	115,300	47,100	10.5	196	225
	20.0	2.0	71,600	103,200	36,800	20.0	179	166
0.4	3.0	13.0	130,900	219,000	58,300	10.0	223	351
0.5	1.0	13.0	116,600	....	82,200	......	228	430
	3.0	5.0	103,900	....	64,000	16.5	166	364
		8.0	127,300	....	93,100	9.0	217	430
		13.0	124,800	....	72,500	11.5	217	364
		20.0	91,400	128,000	75,400	7.0	156	196
	8.0	13.0	127,300	150,900	106,100	6.0	228	321
0.6	3.0	13.0	130,500	197,700	67,300	12.0	228	364
0.7	3.0	13.0	136,000	....	82,200	10.0	288	314
0.8	2.0	2.0	179,100	....	143,800	4.5	518	555
		15.0	222,000	....	199,000	0.0	652	?
	3.0	13.0	122,200	183,600	90,100	15.0	217	430
	10.0	2.0	204,800	....	179,100	3.0	253	?
	20.0	2.0	127,400	114,200	53,600	10.0	207	192
		15.0	112,300	115,100	65,400	18.0	179	179

TUNSTEN-CHROMIUM STEELS

Effect of various heat treatments on hardness

Approx. Composition.			Treatment.	Brinell Hardness.
C.	Cr.	W.		
0.2	3.0	13.0	Quenched at 1200° C., in water................	228
0.4	3.0	13.0	Quenched at 1200° C., in water................	495
0.5	1.0	13.0	Quenched at 1200° C., in water................	460
	3.0	5.0	Quenched at 1200° C., in water................	Cracked
		8.0	Quenched at 1200° C., in water................	418
		13.0	Quenched at 1200° C., in water................	532
		13.0	Quenched at 1200° C., in water................	Cracked
		20.0	Quenched at 1200° C., in water................	302
	8.0	13.0	Quenched at 1200° C., in water................	512
0.6	3.0	13.0	Quenched at 1200° C., in water................	Cracked
0.7	3.0	13.0	Quenched at 1200° C., in water................	Cracked
0.8	3.0	13.0	Quenched at 1200° C., in water................	532
0.5	3.0	13.0	Quenched at 1200° C., after heating 1 minute...	532
			Quenched at 1200° C., after heating 5 minutes ..	555
			Quenched at 1200° C., after heating 10 minutes..	600
			Quenched at 1200° C., after heating 15 minutes..	600
			Quenched at 1200° C., after heating 20 minutes..	600
			Quenched at 900° C., after heating 1 minute....	364
			Quenched at 900° C., after heating 5 minutes....	477
			Quenched at 900° C., after heating 10 minutes...	555
			Quenched at 900° C., after heating 15 minutes...	600
			Quenched at 900° C., after heating 30 minutes...	600
			Quenched at 1200° 3., in air after heating 5 min.	600
			Quenched at 1200° C., in current of air 5 minutes.	600
			Quenched at 1200° C., in oil, 5 minutes.........	578
			Quenched at 1200° C., in water at 15° C., 5 min.	555
			Quenched at 1200° C., in large volume of mercury	555

PART III

THE NON-FERROUS METALS AND ALLOYS AND TIMBER

CHAPTER XVII

THE NON-FERROUS METALS AND ALLOYS

THE PURE METALS

General

510. The Non-ferrous Metals of Industrial Importance. The non-ferrous metals of greatest industrial importance comprise: copper, zinc, lead, tin, aluminum, and nickel. Those of secondary importance include bismuth, antimony, cadmium, mercury and the precious metals—silver, gold, and platinum. A number of these latter metals are chiefly important as alloy elements, and many others such as magnesium, chromium, cobalt, vanadium, tungsten, molybdenum, titanium, etc., have almost no industrial applications except as alloy elements.

The non-ferrous alloys of greatest importance are the alloys of copper with tin (the bronzes), and alloys of copper with zinc (the brasses). Many important special bronzes and brasses are made, however, in which a third alloy element has been included. For this purpose tin or zinc, lead, phosphorus, manganese, aluminum, silicon, iron, and vanadium are most commonly used.

Aside from the bronzes and brasses, copper forms more or less valuable alloys with practically all of the metals above listed; zinc is the principal metal of a number of other important alloys, and the same thing is true of lead, tin, aluminum, nickel and a few others.

The principal non-ferrous metals and alloys are listed in the classification which follows:

CLASSIFICATION OF NON-FERROUS METALS AND ALLOYS

NON-FERROUS METALS

A. Metals of Primary Importance
- (1) Copper
- (2) Zinc
- (3) Lead
- (4) Tin
- (5) Aluminum
- (6) Nickel

B. Metals of Secondary Importance
- (7) Bismuth
- (8) Antimony
- (9) Cadmium
- (10) Mercury
- (11) Silver
- (12) Gold
- (13) Platinum

C. Metals Chiefly Important as Alloy Elements
- (14) Magnesium
- (15) Chromium
- (16) Cobalt
- (17) Vanadium
- (18) Tungsten
- (19) Molybdenum
- (20) Titanium

NON-FERROUS ALLOYS

A. Ordinary Bronzes. Copper-tin Alloys.		
B. Special Bronzes. Copper-tin............	Zinc Lead Phosphorus Manganese Silicon Aluminum Vanadium Nickel	Alloys.
C. Ordinary Brasses. Copper-zinc Alloys.		
D. Special Brasses. Copper-zinc............	Lead Aluminum Manganese Iron Vanadium Phosphorus Silicon	Alloys.
E. Other Binary Alloys of Copper. Copper..	Aluminum Manganese Phosphorus Silicon Vanadium Chromium Tungsten Antimony Bismuth Lead Arsenic	Alloys.
F. Alloys of Zinc. Zinc..................	Lead Tin Antimony Bismuth	Alloys.

G. Alloys of Lead.	Lead	Tin Antimony Bismuth Cadmium Arsenic	Alloys.
H. Alloys of Tin.	Tin	Cadmium Antimony Bismuth Nickel Zinc-lead	Alloys.
I. Alloys of Aluminum.	Aluminum	Zinc Copper Magnesium Copper-zinc Copper-manganese Nickel Tin Manganese Tungsten Chromium Titanium	Alloys.
J. Alloys of Nickel.	Nickel-Copper-Zinc Alloys.		
K. Special Bearing Metals		Bronzes (Ordinary and Special) Lead-antimony Tin-copper-antimony Lead-tin-antimony Lead-copper-antimony Zinc-tin-antimony Lead-tin-bismuth	Alloys.

It would not be justifiable to devote space in the present chapter to a detailed consideration of all of the metals and alloys above listed. In fact, detailed information is not available in the cases of many alloys. A brief treatment of the metallurgy, properties and uses of the more important metals and alloys will be presented, supplemented by a few general statements concerning the properties and uses of the less important ones.

COPPER

511. General. Classification of Commercial Forms of Copper. Copper is, with the exception of iron, the most useful and valuable metal found in nature. Its ores are found in every important country of the world, and native copper is found in enormous quantities in the region abutting upon the south shore of Lake Superior, and, to a lesser extent, in a few other localities. Copper ores exist in a great variety of forms, usually as sulphide or oxide. The greater proportion of the world's supply of copper is derived from copper pyrites.

Owing to the fact that copper exists native and may be reduced from its ores with comparative ease, it has been known and used since prehistoric times. The early Egyptians and some of their Asiatic contemporaries were conversant with the art of extracting copper from its ores and making bronzes therefrom, and the prehistoric nations of America used copper in large quantities. Many articles of copper and bronze made by the Aztecs have survived to the present day and exhibit excellent qualities and very fine workmanship.

The classification of copper most commonly used in the United States is not a particularly rational one, but is one which trade conditions have imposed. The American Society for Testing Materials * recognizes three general classes of American copper, which may be defined as follows:

A. *Electrolytic copper* is copper derived by the electrolysis of a copper sulphate solution with anodes of crude copper and cathodes of pure copper. (Copper migrates from the anode, leaving its impurities behind, and is deposited on the cathode.)

B. *Lake copper* is copper which has originated on the northern peninsula of Michigan, U. S. A. (Southern shore of Lake Superior.)

C. *Casting copper* is more or less impure copper which is either (*a*) fire-refined copper from virgin sources; (*b*) copper electrolytically produced by deposition from impure liquors; or (*c*) copper reclaimed from secondary sources.

Electrolytic copper has in recent years largely replaced all other classes of copper for electrical uses, for alloying purposes, and for all other uses demanding a very pure grade of copper. A large proportion of the electrolytic copper produced is derived from copper pyrites and has previously been smelted and fire-refined. The process of electrolysis results in the recovery of practically all the precious metals commonly present in copper ores, and since this gain, as well as the added market value of electrolytically refined copper, will usually pay the extra cost of electrolytic refining, the amount of casting copper produced is in consequence relatively very small. A considerable portion of even the lake copper is electrolytically refined, either to free it from impurities or to recover the silver content. Nearly 24 per cent of the output of lake copper is thus refined, but the product is usually either mixed with furnace-refined copper or sold as some brand of lake copper.

512. Occurrence in Nature. Ores of Copper. The most important ores of copper are the following:

Native copper occurs in large quantities on the south shore of Lake Superior in the upper peninsula of Michigan. It is also found in New

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* Proceedings, Vol. 13, 1913, p. 206.

Mexico, in Chili, and in South Australia. The lake copper which has always been an important factor in the copper industry of the world is from this source.

Copper pyrites or *chalcopyrite* ($CuFeS_2$), is the ore from which the greater proportion of the world's copper supply is derived. It contains when pure, 34.4 per cent of copper, often contains both silver and gold, and is generally associated with iron pyrites. It occurs in the United States in Vermont, Virginia, Georgia, Tennessee, Alabama, and Montana. It also occurs in Spain, Portugal, France, Germany, Austro-Hungary, England, Ireland, Italy, Sweden, Norway, Russia, Newfoundland, Canada, Cuba, Peru, Australia, and Africa.

Chalcocite or *copper glance* (Cu_2S) contains 79.89 per cent copper. It occurs in large quantities in Montana, Arizona, New Mexico, and Texas, and is also found in England, Italy, Russia, Chili, and Australia.

Bornite or *erubescite* (Cu_3FeS_3) contains on the average 55.6 per cent of copper. It generally occurs intermixed with chalcopyrite and chalcocite, and is doubtless a decomposition product, as is shown by its variable content of copper, ranging between 42 and 70 per cent. It occurs in Montana, also in England, Italy, and Chili.

Cuprite (Cu_2O) contains 88.8 per cent of copper. It is abundant in New Mexico and Arizona and in South Australia. It occurs also in Chili, Colombia, and Russia. *Tile ore* is an intimate mixture of cuprite and limonite. Cuprite is a decomposition product of sulphur compounds of copper.

Melaconite or *black copper* contains 79.8 per cent of copper, but usually occurs contaminated with oxides of iron and manganese. Like cuprite, it is a decomposition product of sulphides and was formerly found abundantly in Tennessee, North Carolina, and Virginia. The black copper was long ago exhausted, however, and the original sulphides are now being mined in some of the old workings.

Malachite ($CuCO_3$, $Cu(OH)_2$) contains 57.33 per cent of copper and is another decomposition product of sulphides. It is abundant in Eastern Russia, in Chili, and in South Australia, and has been encountered in Arizona and New Mexico.

Azurite or *chessylite* ($2CuCO_3$, $Cu(OH)_2$) contains 55.16 per cent of copper and is another decomposition product of the sulphides. It generally occurs with malachite, and has been mined principally in France (at Chessy) and in Russia. It has also been found with malachite in Arizona and New Mexico.

Chalcanthite or *copper vitriol* ($CuSO_4+5H_2O$) is a crystalline decomposition product containing 25.4 per cent of copper, or is found in solution in the waters of mines that are working on mixtures of sulphide ores and iron pyrites, etc.

Atacamite ($CuCl_2+3Cu(OH)_2$) contains 59.4 per cent of copper and occurs plentifully in Chili and Peru.

Chrysocolla is a hydrated silicate of copper containing an average of 39.9 per cent of copper. It is a decomposition product of sulphides and is generally associated with malachite. It occurs plentifully in Eastern Russia and in Chili.

Covellite or *indigo copper* (CuS) contains 66.0 per cent of copper and is found to a considerable extent in Chili.

Bournonite ($PbCuSbS_3$), enargite ($[4CuS+Cu_2S]As_2S_3$), and fahlore or tetrahedrite ($4[Cu_2S, FeS, ZnS, Ag_2S, Hg_2S]Sb_2S_3, As_2S_3$) are ores of rare occurrence and little commercial importance.

513. The Extraction of Copper from its Ores. The metallurgy of copper is very complex on account of the great variety of ores used and the frequent necessity of providing for the recovery of not only copper, but also the precious metals which occur in copper ores. The number of metallurgical methods of extraction of metallic copper is therefore very large.

The chief sources of copper have been shown to be ores which are essentially more or less complex sulphides, ores which, although originally sulphides, have by atmospheric agencies been altered to oxides and carbonates, and native copper ores wherein the copper exists as free metal. (A considerable proportion of the copper of commerce is derived from secondary sources, i.e., it is remelted or resmelted scrap.)

Sulphide ores are usually treated by one of three general processes which will be briefly considered under the heads: (*A*) Roasting, smelting, and converting, (*B*) pyrite smelting, and (*C*) alternate oxidation and reduction. When the ores are wholly oxidized the copper may be recovered by a process of direct reduction.

With only minor exceptions, all of the products from the foregoing processes must be further subjected to a refining treatment before being marketed. Only two general methods of refining possess any present importance. These are (1) electrolytic refining, and (2) fire or furnace refining. The former is now the method most commonly applied.

Aside from the above-mentioned methods of derivation of copper, which may all be characterized as *dry methods*, *wet* or *chemical methods*, depending upon the getting of the copper into aqueous solution by means of suitable solvents and subsequently recovering it from the solution by electrolysis or by the use of suitable precipitants, have been experimented with for many years and perhaps may now be considered to have attained a position of some commercial importance.

In the following paragraphs the several processes of derivation of copper above mentioned will be briefly considered.

Roasting, Smelting and Converting. Roasting has for its principal objects the burning of the sulphur contents of the ore to sulphur dioxide (SO_2), which passes away as gas, and the changing of the metal with which the sulphur was combined into an oxide. No effort is made, however, to eliminate entirely the sulphur, or completely oxidize the metal, since some sulphur and lower oxides are desirable in the subsequent smelting operation.

Two methods of roasting which have been practiced for generations are *heap roasting* and *stall roasting.* Heaps are built up on a bed of fuel in such a manner that the coarser lumps are in the center of the pile, while the smaller ore, in continually diminishing sizes, forms the exterior. The heap is covered with a layer of fines or concentrates. The fuel is cordwood, brushwood, heather, or coal, and passages are provided in the bed for draft. The shape of the heap is that of a truncated square pyramid, and its dimensions may be anything up to about 85 to 100 feet long, 40 to 50 feet wide, and 8 feet 6 inches high. According to the amount of copper and sulphur in the ore, and the height of the heap, the time required for roasting may be anything from about forty days to more than one hundred days.

Stall roasting resembles heap roasting except that the heaps are enclosed within low masonry walls on three sides. Stacks are usually provided to increase the draft, the top of the pile being made air-tight by a layer of fines, or a cover provided for the entire stall. In stall roasting the time is considerably shorter than with heap roasting, and a smaller proportion of the ore is insufficiently roasted.

Roasting in reverberatory furnaces similar to the furnaces used for smelting hereinafter described (except that, being worked at lower temperatures, the firebox is much smaller in proportion to the size of the hearth) has been practiced for many years. The ore must be comparatively finely divided (a considerable proportion of it much finer than ¼ inch), and this may mean an additional expense for crushing and grinding if this has not been previously required for purposes of mechanical concentration. Nevertheless, a considerable saving in time and fuel is effected by the use of the reverberatory roasting furnace in preference to the older methods of roasting out of doors in heaps or stalls. On account of the severe labor involved in stirring or rabbling the ore, mechanical rabbling devices are often employed.

The most modern type of roasting furnace, Fig. 306, is a shelf furnace containing six circular hearths one above the other. The hearths are provided with openings alternately at the center and at the periphery to permit of the descent of the ores. A vertical hollow shaft traverses the center of the furnace carrying rabbles which are set to move the material toward the outlet opening of each hearth. The air required for combustion is forced in by a fan at the bottom, and the products of combustion (principally sulphuric acid gas), escape through a flue provided at the top. The ore to be roasted is delivered by hoppers to a drying hearth on the top of the furnace; rabbles gradually transfer it to the peripheral opening leading to the top roasting hearth, and by the motion of successive sets of rabbles it is gradually dropped from hearth to hearth, falling alternately at the center and the periphery, until it leaves the lowest hearth in a roasted condition. A temporary firebox must be used to heat a cold furnace to the required temperature, after which raw ore is charged and firing kept up until calcination has commenced and the ores have reached a dull red heat. Calcination thereafter continues by the combustion of the sulphur of the ore without any extraneous fuel. The Herreshoff furnace illustrated is provided with an air-cooling arrangement, air under pressure being forced up the central tube and through the hollow arms which carry the rabbles. Any desired portion of this heated air may be taken from the top of the furnace and returned to the lowest hearth, thus raising the working temperature and making possible the roasting of ores quite low in sulphur without extraneous fuel.

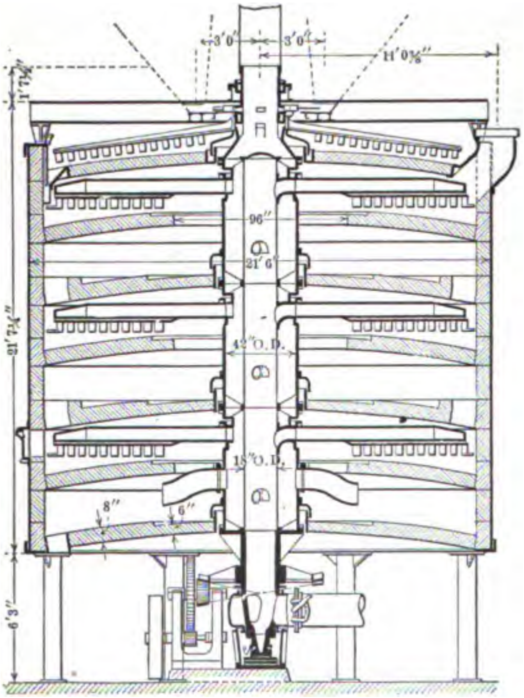
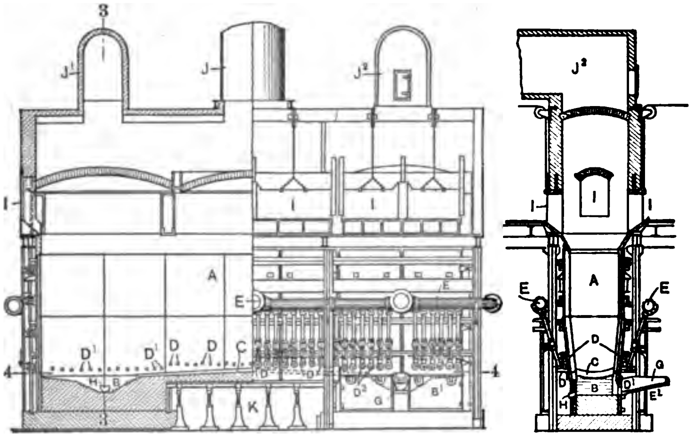


Fig. 306.—Herreshoff 6-Hearth Ore Roasting Furnace.

Smelting of copper ores has for its object simply the concentration of the ore by removal of the earthy portion or gangue, in order that only the metallic portion may have to be treated by the subsequent more expensive refining process. It is not possible with sulphide ores to derive metallic copper as metallic iron is derived in the blast furnace, because, though the smelting operation is similarly conducted as a reducing process, the copper did not originally exist as an oxide. Iron pyrites and other sulphide minerals are not rejected but, upon melting, join the metallic portion of the material in the furnace. It is only because some portion at least of the undesirable metallic minerals have by the preliminary process of roasting been changed into the oxidized condition that their removal in the slag is in any degree possible.

The ultimate product of the smelting operation is therefore a large amount of worthless slag, made up principally of silica combined with ferrous oxide, alumina, and lime from the flux, and a small metallic portion called *matte*, which is essentially a mixture of metallic sulphides of copper, iron, and other metals originally present in the ore.



LONGITUDINAL SECTION

TRANSVERSE SECTION

Fig. 307.—Water-jacketed Copper Blast Furnace. (Peters.)

The smelting of copper ores is accomplished in one of two general types of furnace, viz., the *blast furnace* and the *reverberatory furnace*. The two methods of smelting will be briefly considered separately.

A modern type of copper blast furnace is illustrated by Fig. 307. This is a 56-inch by 51-foot furnace (inside measurements at tuyere level), and has an average daily capacity on roasted ore of about 1600 tons of charge. Much larger furnaces have been built by increasing the length without materially increasing the width between tuyeres, the number of crucibles and spouts being increased. The furnace of Fig. 307 has two crucibles *B* and *B′*, located near the ends of the shaft *A*. Sets of tuyeres *D*, *D′*, and, D^2, penetrate the side walls of the shaft, the crucible tuyeres D' and D^2 being at a slightly lower level than the hearth tuyeres D. The bottom of the shaft slopes in each direction from the center, so that the molten metal flows into the crucibles. The crucibles are provided at their front ends with slag spouts *G*, which are trapped so that the outlet is considerably higher than the opening through the crucible wall. Slag flows continuously, and the blowing of the blast out through the slag spout is prevented by the head of slag maintained above the slag outlet by the trap. At the opposite end of the crucibles tap holes *H* are provided which allow a continuous stream of metal to flow into large forehearths.

The mechanical operation of the furnace involves charging of the ore and fuel, removal of the slag and the matte, the collection of the flue dust and the volatilized metals, and the control of the blast.

Charging is done by means of side-dump cars through the charging doors *I*, ore, flux, and fuel being charged alternately. The slag is granulated by a stream of water which also serves to carry the slag to the dump. The matte is received in a cylindrical forehearth which holds a great quantity of metal and keeps it molten. The forehearth is tapped at intervals into a ladle which conveys the matte to the converters.

The flue dust is recovered by dust catchers in the gas downtake, just as in the case of the iron blast furnace, and is subsequently resmelted, usually after having been briquetted. The volatilized metals are recovered by straining the gases through cloth. The equipment used for this purpose, the bag-house, will be mentioned hereinafter in connection with lead smelting.

The blast has until recently been derived most often from rotary impeller blowers, but with the increased pressure and air-volume requirements of larger furnaces positive piston blowers or blowing engines are now preferred. The blast pressure utilized by the furnace above illustrated is about 2½ pounds per square inch.

In the reverberatory furnace the fuel and ore are separated, not mixed as in the blast furnace, the fuel (usually either a long-flaming bituminous coal, petroleum, or dry pulverized coal), being burned in a separate firebox, or introduced by burners at one end, and the ore is heated by the flame passing over its surface and the heat reflected from the arch of the furnace.

Fig. 308 illustrates a large modern reverberatory furnace in which coal fuel is used. It is provided with a firebox 9 by 12 feet inside dimensions, a cross-wall, *b*, of brick divides it into two compartments, each of which is provided with firing holes in the roof and air inlets for forced draught. The hearth is 17 feet wide, about 44 feet long, and is served by four working doors *d*, and five charging holes in the arched roof. A door *c* is provided in the flue wall for skimming the bath. The arch and side walls, as well as the fire bridge, are of firebrick, while the hearth bottom is of quartz sand 24 to 36 inches deep, sintered in place. This size of furnace will smelt something like 200 tons of raw ore per day, the fuel requirement being about 1 ton of coal per 5 tons of ore charged.

The reverberatory process is not a reducing process as operated for matte production. The charge must be in a condition favorable to quick melting, and therefore fine ore, not lumps, composed of silicious sulphide concentrate, roasted concentrate, and flue dust are used. Several ore charges are allowed to melt down, and then the matte is tapped as the converters require it. The slag is tapped off at a higher level from time to time, but neither slag nor matte is ever entirely tapped out. The introduction of oil fuel in certain reverberatory furnaces in this country has made possible the smelting of higher silica ores without requiring that the charge be in so finely divided a state.

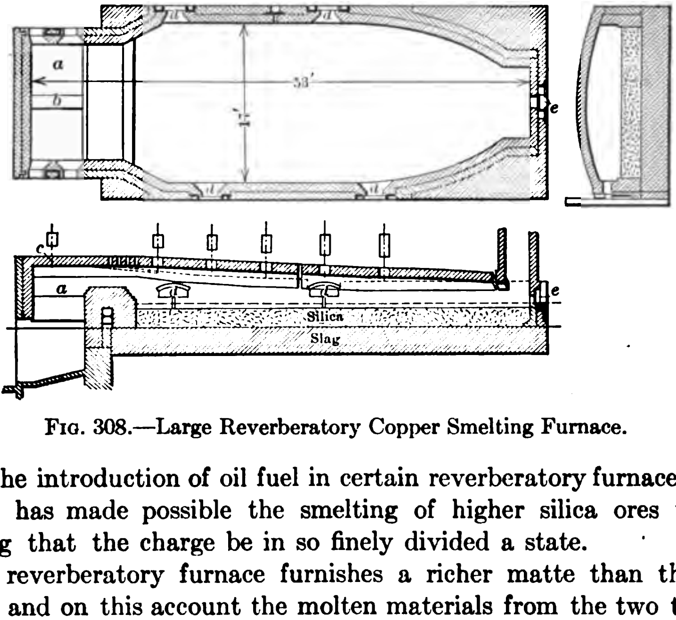


Fig. 308.—Large Reverberatory Copper Smelting Furnace.

The reverberatory furnace furnishes a richer matte than the blast furnace, and on this account the molten materials from the two types of furnaces are sometimes mixed before conversion in the Bessemer converter.

The conversion of the matte into metallic copper is accomplished in a Bessemer converter, the principle of operation of which does not differ essentially from that of the ordinary Bessemer steel converter. The converter is always side blown, however, and at the present time the lining is invariably a basic one made of magnesite brick. Fig. 309 illustrates a modern type of copper converter of the upright type. Another common form of converter has the form of a horizontal cylinder. It is mounted on trunnions, however, and operated in much the same manner as the upright converter.

There are two main stages in the operation of Bessemerizing copper mattes. The first is essentially the elimination of the iron sulphide; the second the final sulphur elimination. During the first stage the oxygen of the air blown into the molten matte forms oxides of iron, sulphur, and copper, and the latter immediately reacts with the remaining iron sulphide, reforming copper sulphide with the production of more iron oxide. The iron oxide now reacts with the silica which has been introduced with the charge or during the blow, and produces a great quantity of ferrous silicate slag which must be poured off at the end of this stage. The sulphur oxidizes to SO_2, which is driven off.

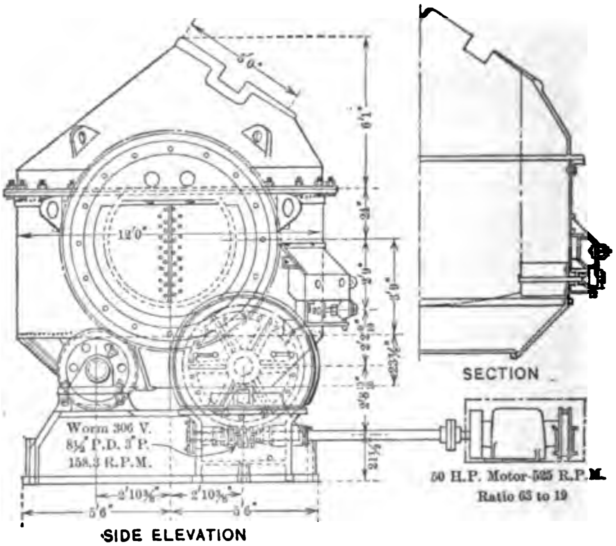


Fig. 309.—Modern Upright Copper Converter.

The product of the first stage of the operation is a "white metal," which may be considered to be practically pure copper sulphide.

The white metal is now blown to produce blister copper, the sulphur being eliminated by the action of copper oxide, first produced, on the copper sulphide present. Blowing to white metal requires about fifty to sixty minutes, and metallic copper is obtained after about sixty minutes' more blowing. The progress of the operation is judged principally by the appearance of the converter flames.

Pyrite Smelting. The process of pyrite smelting is one developed in the United States under circumstances permitting of the exclusive use of a highly pyritous ore. The term "pyrite smelting" is applied to the smelting of a pyritous ore mainly by the heat of combustion of its own sulphide constituents. The great advantage of pyrite smelting, when practicable, is that it is a process of smelting raw ore, and the expense of the usual roasting treatment is therefore saved. Pyrite smelting is practiced only by a few American smelters, and little will here be said concerning the process.

Ores suitable for pyrite smelting contain a large amount of iron sulphide, and the iron pyrites (FeS_2) loses part of its sulphur by dissociation in the upper portion of the blast furnace, leaving iron sulphide (FeS). The iron sulphide now reacts with oxygen and silica, forming a ferrous silicate slag and liberating sulphur dioxide. A considerable amount of uncombined silica or quartz is a necessary part of the charge, and the degree of concentration accomplished is controlled by varying the quartz charge.

Pyrite smelting requires more flux than ordinary smelting, on account of the slag formed. It also makes more slag, the metal loss is greater, and a stronger blast pressure is called for, but these disadvantages are more than offset by the advantages gained.

Alternate Oxidation and Reduction. This process is the old Welsh process, still used to some extent abroad but long ago abandoned in this country. It consists in a long series of alternate calcinations and fusions in the reverberatory furnace. The removal of impurities is imperfect, but the sulphur is gradually driven off and the other impurities become segregated in a portion of the product. This is the origin of the English " best selected " copper.

Refining of Blister or Coarse Copper. Electrolytic refining has come to be the method by which all the finer grades of copper, such as are used for electrical purposes, are refined. Nevertheless, the older method of refining in a reverberatory furnace still possesses some commercial value and will be briefly considered.

Fire refining is based upon the scorifying effect of cuprous oxide upon base metals contained in a batch of molten copper. Air is blown upon a bath of molten coarse copper contained in the hearth of a reverberatory furnace. Cuprous oxide is very rapidly formed, and becomes dissolved in the bath. A very active oxidizing agent is thus intimately mixed with all of the molten material; the impurities become oxidized and form a slag which may be skimmed off, while the cuprous oxide is reduced to metallic copper. An excess of cuprous oxide usually remains after the removal of impurities has been carried to the practicable limit (traces always remain), and this must subsequently be reduced by the use of a layer of charcoal or coke spread over the molten metal. Green poles are then thrust beneath the surface and in this way the dissolved cuprous oxide is gradually reduced until the oxygen content does not exceed about

0.05 to 0.07 per cent. No recovery of precious metals is possible, and the copper bars formed by casting the product are still relatively impure compared with electrolytic copper.

Electrolytic refining has displaced other methods of refining, primarily because the product is purer than is otherwise generally obtainable. The fact that the precious metals are separated by the same operation is an important consideration, however.

The fundamental principles of the process of electrolysis have been explained above and need not be elaborated upon. The crude copper cast into anode plates is electrolyzed in a strongly acid copper sulphate solution. Copper is deposited on the cathode, while the impurities, including the precious metals, are insoluble in the electrolyte and fall to the bottom, forming slimes which are subsequently refined for recovery of silver, gold, etc. The purity of the cathode copper is dependent only upon the character of the electrolyte, though there is a practical limit to the degree of impurity of the anode copper.

Electrolytic cathodes commonly contain about 99.95 per cent copper, the adulterants being principally hydrogen, with perhaps 0.02 per cent of metallic impurities. The cathodes are not generally marketed without remelting in a reverberatory furnace, because their form is not one which is suitable for shipment, small pieces being easily broken off. The remelting usually partakes of the nature of a fire refinement in some measure, but this is only because of the contamination of the copper inevitably incidental to remelting. The extraordinary conductivity of cathode copper is slightly impaired by fire refinement.

Lake copper is derived from low-grade native-copper deposits which are mechanically concentrated after crushing. The resultant "mineral" contains about 85 per cent of copper. This is melted in reverberatory furnaces, the slag skimmed off, and the metal is fire refined by the method above described. In certain cases where the impurities, particularly the arsenic, run rather high, and where the content of precious metals is sufficient to pay the cost, electrolytic refining of lake copper is practiced. The resultant product is marketed as lake copper—not as electrolytic copper, however. Unless the metal is electrolytically refined, lake copper is usually sufficiently alloyed with arsenic, or phosphorus, aluminum, silica, etc., to be rendered unfit for electrical purposes because of low conductivity. The presence of these elements is not necessarily undesirable, however, because they are for the most part helpful in developing desirable mechanical properties.

Wet or *chemical methods* of derivation of copper (sometimes called *hydrometallurgical methods* or *copper leaching*) from low-grade ores or tailings are now being experimented upon by most of the important copper-producing companies of this country. The process is still in an experimental stage and details of practice vary considerably.

In general the practice usually consists in subjecting the ore to lixiviation by sulphuric acid in tanks or vats, no great difficulty being encountered in getting the copper into solution.

The precipitation of the dissolved copper is an operation which has caused more difficulty than the first stage of the process. The recovery of the copper by electrolysis is being tried extensively with considerable success. Recently the use of insoluble anodes of fused magnetite, and the introduction of sulphur dioxide gas into the electrolyte, thus reducing the current requirements, have been found to offer distinct advantages.

Aside from the use of the electrolytic method, copper is most frequently recovered from solution by the use of sponge iron as a precipitant. The latter is obtained by a roasting of pyrites, followed by reduction of the iron oxide formed. The sulphur driven off in roasting the pyrite is used to make acid solvent.

514. The Properties and Uses of Copper. The properties of copper which possess the greatest practical importance are its electrical conductivity (or conversely, resistivity), and its tensile properties. Since something over 50 per cent of all the copper consumed in this country is used for electrical purposes, high conductivity may properly be considered to be the first requisite of nearly all high-grade copper and tensile properties are next most important.

Electrical Resistivity

The maximum resistivity of various classes of copper and copper products permitted under the standard specifications of the American Society for Testing Materials * is as follows, the resistivity being expressed in international ohms per meter-gram at 20° C.:

Low-resistance lake copper wire bars (annealed)		0.15535
High-resistance lake copper		0.15694
Electrolytic copper wire and cakes, slabs, and billets for electrical purposes		0.15535
Electrolytic copper ingots and ingot bars, cakes, slabs, and billets not intended for electrical uses		0.15694
Hard-drawn copper wire	diameters 0.460 to 0.325 in.	0.15775
	diameters 0.324 to 0.040 in.	0.15940
Medium-hard drawn copper wire	diameters 0.460 to 0.325 in.	0.15694
	diameters 0.324 to 0.040 in.	0.15857
Soft or annealed copper wire		0.15614

The electrical conductivity is principally dependent upon the purity of the copper, and the specifications for lake and electrolytic copper therefore contain the following stipulations as to the minimum metal content:

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* Year-book. 1914.

Class of Copper	*Minimum Metal Content*
Low-resistance lake copper.....	99.88 (silver counted as copper)
High-resistance lake copper....	99.88 (silver and arsenic counted as copper)
Electrolytic copper (all shapes).	99.88 (silver counted as copper)

Tensile Properties

The tensile properties of hard-drawn, medium hard-drawn, and soft or annealed copper wire of various sizes are required to satisfy the following specifications of the American Society for Testing Materials:

Diameter. Inches.	Area. Cir. Mils.	Hard-drawn Wire.		Medium Hard-drawn Wire.			Soft Wire.	
		Minimum Tensile Strength. Lbs. per Sq.in.	Minimum Elongation. Per cent in 10 Ins.	Tensile Strength.		Minimum Elongation. Per cent in 10 Ins.	Minimum Tensile Strength. Lbs. per Sq.in.	Minimum Elongation. Per cent in 10 Ins.
				Minimum Lbs. per Sq.in.	Maximum Lbs. per Sq.in.			
0.460	211,600	49,000	3.75	42,000	49,000	3.75	36,000	35
0.410	168,100	51,000	3.25	43,000	50,000	3.60	36,000	35
0.365	133,225	52,800	2.80	44,000	51,000	3.25	36,000	35
0.325	105,625	54,500	2.40	45,000	52,000	3.00	36,000	35
0.289	83,520	56,100	2.17	46,000	53,000	2.75	37,000	30
0.258	66,565	57,600	1.98	47,000	54,000	2.50	37,000	30
0.229	52,440	59,000	1.79	48,000	55,000	2.25	37,000	30
			Per cent in 60 Ins.			Per cent in 60 Ins.		
0.204	41,615	60,100	1.24	48,330	55,330	1.25	37,000	30
0.182	33,125	61,200	1.18	48,600	55,660	1.20	37,000	30
0.165	27,225	62,000	1.14	......	......	......	37,000	30
0.162	26,245	62,100	1.14	49,000	56,000	1.15	37,000	30
0.144	20,735	63,000	1.09	49,330	56,330	1.11	37,000	30
0.134	17,956	63,400	1.07	......	......	......	37,000	30
0.128	16,385	63,700	1.06	49,660	56,660	1.08	37,000	30
0.114	12,995	64,300	1.02	50,000	57,000	1.06	37,000	30
0.104	10,815	64,800	1.00	......	......	......	37,000	30
0.102	10,404	64,900	1.00	50,330	57,330	1.04	38,500	25
0.092	8,464	65,400	0.97	......	......	......	38,500	25
0.091	8,281	65,400	0.97	50,660	57,660	1.02	38,500	25
0.081	6,561	65,700	0.95	51,000	58,000	1.00	38,500	25
0.080	6,400	65,700	0.94	......	......	......	38,500	25
0.072	5,184	65,900	0.92	51,330	58,330	0.98	38,500	25
0.065	4,225	66,200	0.91	......	......	......	38,500	25
0.064	4,096	66,200	0.90	51,660	58,660	0.96	38,500	25
0.057	3,249	66,400	0.89	52,000	59,000	0.94	38,500	25
0.051	2,601	66,600	0.87	52,330	59,330	0.92	38,500	25
0.045	2,025	66,800	0.86	52,660	59,660	0.90	38,500	25
0.040	1,600	67,000	0.85	53,000	60,000	0.88	38,500	25
0.021	......	......	......	......	......	......	38,500	25
0.020	......	......	......	......	......	......	40,000	20
0.003	......	......	......	......	......	......	40,000	20

The gradual increase in the tensile strength requirement and the decrease in ductility called for, as the size of wire becomes smaller, is in conformity with the well-known fact that the tensile strength increases rapidly, and ductility decreases, as the amount of cold working to which the copper is subjected in drawing increases. The effect of partial and complete annealing is also recognized by the slightly lower strength values and slightly higher degree of ductility called for in the case of the medium hard-drawn wire, and the much lower strength and very much greater ductility required in the case of the soft wire.

The yield point of copper wire does not appear distinctly in tests, and the stress-strain curve exhibits no sudden break, as is the case with mild and medium steels. Tests made by members of the committee which framed the above specifications established the average value of the elastic limit of hard-drawn wires at 55 per cent of the specified ultimate tensile strength in the case of the wires more than 0.324 inch in diameter, and 60 per cent in the case of wires less than 0.325 inch in diameter. For medium hard-drawn wire the average value of the elastic limit was found to be 50 per cent of the specified tensile strength. The modulus of elasticity of drawn copper is usually found to be in the neighborhood of 16,000,000 pounds per square inch.

The tensile properties of copper in forms other than wire are not well known, nor are they commonly specified at all. Hot-rolled plate shows an elastic limit usually not above 7000 or 8000 pounds per square inch, and an ultimate tensile strength of from 30,000 to 40,000 pounds per square inch. By finishing cold or by cold hammering its elastic limit may be doubled, or more than doubled, while the tensile strength is increased in a lesser degree.

Uses of Copper

The relative proportions of the copper output of the United States applied to various classes of uses are indicated by the following Government statistics:

FORMS IN WHICH COPPER WAS CAST IN 1913, PERCENTAGE OF TOTAL *

	Per cent
Wire bars (used principally for electrical purposes)	58
Ingots and ingot bars (for castings and for brass and bronze industries)	23
Cakes (principally for rolled copper)	9
Cathodes (principally for brass and bronze industries)	8
Other forms	2
	100

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* "Mineral Resources," 1913.

According to the figures of Aron Hirsh & Sons in their "Copper Statistics for 1913" * the consumption of copper in the United States was divided as follows:

	Per cent
Electrical industry (including copper wire)	52.1
Brass mills	28.7
Copper sheets	13.7
Miscellaneous (chiefly castings and alloys)	5.5
	100.0

Production of Copper

515. Statistics of Copper Production. The total production of copper from primary sources in the United States, as compiled from the smelter returns for the last four years, is reported as follows: *

	Pounds
1910	1,080,159,509
1911	1,097,232,749
1912	1,243,268,720
1913	1,224,484,098

Of the primary copper produced in 1913 about 86.7 per cent was electrolytic copper, about 9.6 per cent lake copper, and about 3.7 per cent casting and pig copper. Of the total production of copper including (1) that from primary sources, and (2) that produced from secondary sources by either regular refiners or by plants that treat secondary materials exclusively in the production of copper and copper alloy products, the proportion of secondary copper from all sources amounts to about 14.4 per cent. (The production of lake copper in 1913 was abnormally low because of unfavorable labor conditions in the lake district. In 1912 and 1911 the proportion of lake copper was about 15 per cent of the total production of primary copper.)

ZINC

516. General. Commercial Forms of Zinc. After copper and lead, zinc is the next most important of the non-ferrous metals. It occurs in some measure in almost every important political division of the world, usually as a sulphide, a carbonate, or a silicate. It is used not only as metallic zinc, in which form it is known to trade as "spelter," but also in the form of zinc dust, which is formed in the distillation of zinc, and as zinc pigments, such as zinc oxide, leaded zinc oxide, and

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* "Mineral Resources," 1913.

lithopone. A considerable proportion (about 25 per cent) of the zinc used commercially is derived from secondary sources, and not directly from ores.

517. Occurrence in Nature. Ores of Zinc. The most important ores of zinc are zinc blende, calamine, and hemimorphite.

Zinc blende or *sphalerite* (ZnS) is at present the main source of zinc production. It contains 67.15 per cent of zinc when pure, but usually contains manganese, iron, cadmium, etc. *Marmatite* is a common variety containing 10 per cent or more of iron as sulphide. Zinc blende is found in practically every one of the European States, also in Asia, Africa, Australia, South and Central America, Canada, and—in the United States—in Arkansas, Utah, New Mexico, Tennessee, Virginia, Kentucky, Iowa, New Jersey, Missouri, Pennsylvania, Wisconsin, and Colorado.

Calamine or *zinc spar* ($ZnCO_3$) was formerly the chief source of zinc, but has been relegated to a secondary position, owing to the exhaustion of many deposits. Calamine is rarely pure, but contains as a rule carbonates of cadmium, iron, and manganese. When pure, it contains 52 per cent of zinc, while the presence of other carbonates may reduce the zinc content below 40 per cent. Calamine occurs almost as universally as does zinc blende, and is found, or at one time was found, in most of the districts in which blende occurs.

Hemimorphite or *zinc silicate* ($Zn_2SiO_4+H_2O$) contains 53.7 per cent of zinc when pure, and is often intermixed with, or underlies, deposits of calamine. It occurs in Altenburg, in Sardinia, Spain, Tunis, and—in the United States—in New Jersey, Pennsylvania, Missouri, Kansas, Virginia, and Wisconsin.

Franklinite ($(Fe, Zn, Mn)O, (FeMn)_2O_3$), *willemite* ($Zn_2SiO_4$), *zincite* or *red zinc ore* (ZnO), and *hydrozincite* or *zinc bloom* ($ZnCO_3+2ZnH_2O_2$) are comparatively rare zinc ores of lesser commercial importance.

518. Extraction of Zinc from its Ores. The chemical properties of zinc are so different from those of other common metals that the metallurgical methods by which metallic zinc is derived from ores are unique ones, and are, furthermore, complex, and metallurgically imperfect. Whatever the original state of the zinc in the ore, it must be in the form of an oxide before the metallic zinc is obtainable. In this form it may be reduced by carbon at high temperatures, but this temperature is above the volatilizing point of the metal, so that it is always obtained as a vapor which must be condensed. Moreover, condensation of zinc vapor must be accomplished at a temperature above the point of fusion if the metallic zinc is to be obtained in the more commonly useful commercial form as spelter. Otherwise, i.e., by condensation at a temperature which produces solid instead of liquid metal, a powder called *zinc dust* or *zinc fume* is derived. This dust has certain special uses, but oxidizes very readily and cannot be remelted and cast to form spelter. A further complication is introduced by the fact that zinc cannot be reduced in the presence of even minute quantities of carbon dioxide without becoming oxidized, and it is therefore essential that the reduction be accomplished in the presence of an excess of carbon and in a closed retort without access of air.

Preliminary Treatment of Ores, Concentration, Calcination, and Roasting. All ores must be crushed to a finely divided state before being otherwise treated. Some measure of mechanical concentration is usually accomplished at this stage, and recently so-called *flotation* concentration has been widely adopted. In this process the ore is reduced to a six-mesh size and the tailings from the jigs are finely pulverized, thickened to three parts water to one part ore, mixed with a small quantity of oil and sulphuric acid, and agitated in a tank. A float concentrate is then taken off, the gangue goes to a second-treatment tank, where the process is repeated, and finally to a third treatment tank, where the final concentrate is taken off and the remaining gangue discharged as worthless tailings.

Calamine (zinc carbonate) and zinc silicate ores usually must be calcined prior to reduction and distillation, for the purpose of driving off the carbonic acid and water. Some anhydrous calamines and silicates are not calcined, but are reduced in the raw state. All American ores of these classes are so handled. Calcination, when practiced, is accomplished in shaft furnaces, resembling lime kilns, and the operation is quite analogous to lime burning.

Blende must be roasted prior to reduction and distillation, in order to convert the sulphide into oxide as completely as possible. Any zinc remaining as a sulphide is lost in the retort residues after distillation. The roasting operation results in obtaining zinc oxide, and is attended by the derivation of quantities of sulphur dioxide gas, which latter is usually collected and neutralized, because of its destructive attack upon vegetation if allowed to escape freely near the ground level. Not infrequently the SO_2 is collected and used in a by-product sulphuric acid plant.

Many forms of furnaces have been employed in roasting blende, but for the most part modern roasting furnaces are reverberatory multiple-hearth furnaces fired by coal or gas. Fig. 310 is a transverse section of such a furnace, the three lower hearths of which are muffled, i.e., the charge is out of contact with the products of combustion. Mechanical means for agitating the material and the distribution and removal of same is provided.

Distillation and Condensation. The retorts in which distillation is accomplished are usually of cylindrical form, are about 8 to 10 inches in internal diameter, about 4 feet 6 inches long, closed at one end and provided with a connection with the condenser at the other end. Retorts are made with great care from specially selected clays and are molded under heavy pressure. Before firing, they are carefully dried, and when placed in the furnace must be red hot. The condensers are short clay cylinders or cones, which are attached to the end of the retort in such a manner that they may be easily and quickly detached for emptying, although luted tight to the retort while in use.

The distillation furnace consists of a long masonry chamber which is usually built with two parallel compartments, the side walls of which are simply open frames of firebrick. The retorts are placed in these chambers, the closed end being supported by projections on the longitudinal division wall, while the open end is carried by the brick frame-work of the face. The retort is so supported as to incline slightly downward and outward, and the condenser projects beyond the face of the brickwork, the space around it being tightly luted with clay or clay and coal. Fig. 311 shows a simple form of distillation furnace which is much used. The furnace may be heated by coal burned on grates beneath, but is now commonly heated by gas, which is admitted at one end. Air for combustion is admitted at different points along the length of the furnace in order that the gas may be burned gradually. The furnace illustrated has 864 retorts, six rows high. Sometimes the number of retorts may exceed 1000 to a furnace.

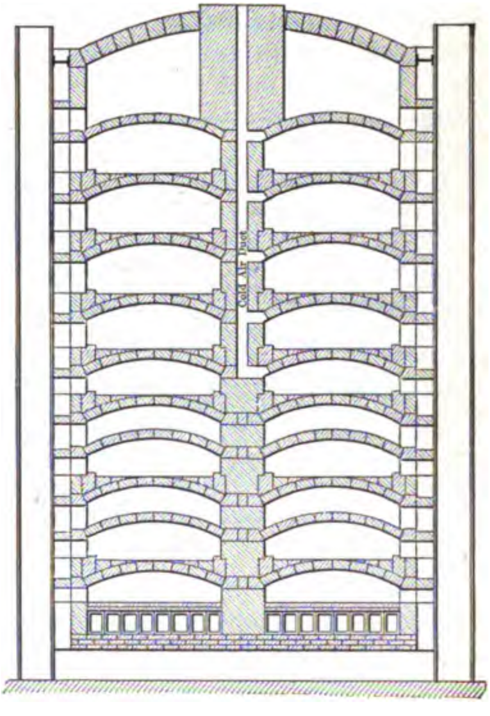

FIG. 310.—Hegeler Muffle Zinc Roasting Furnace.

The operation of the process of distillation and condensation is briefly as follows:

THE STRENGTH OF CAST ZINC

Grade.	Analysis per cent.			Ultimate Tensile Strength Lbs. per Sq.in.			Bending Modulus of Rupture Lbs. per Sq.in.		
	Pb	Fe	Cd	Max.	Min.	Ave.	Max.	Min.	Ave.
1. High grade......	0.041	0.014	0.000	8,326*	4,098	6,262	12,150	11,110	11,630
2. High grade......	0.040	0.016	0.000	4,973	4,109	4,330	11,060	10,040	10,570
1. Intermediate....	0.194	0.016	0.000	5,451	3.740	4,340	10,660	9,640	10,160
2. Intermediate....	0.190	0.017	0.000	6,088	4,487	5,095	13,820	9,930	12,360
1. Brass special....	0.474	0.013	0.000	13,821*	10,125*	11,980*	22,220*	11,620	16,550*
2. Brass special....	0.484	0.031	0.000	5,351	4,098†	4,330†	16,260*	8,580†	13,110
1. Prime western No. 1.........	1.190	0.032	0.250	10,444*	4,198	7,710	12,830	8,440†	11,020
2. Prime Western No. 1.........	1.420	0.087	0.079	4,377	2,984†	3,700	10,750	9,400†	10,050†
1. Prime Western No. 2.........	0.680	0.010	0.274	13,543*	7,122	10,800	18,390*	13,300	16,250*
2. Prime Western No. 2.........	1.150	0.011	0.046	5,331	3,640	4.670	11,350	9,390†	10,370
Dross..........	2.090	3.510	0.043	8,136	6,326	7,340	16,100	13,750	15,300

Grade.	Total Deflection in Bending on 12-inch Span Inches.			Compressive Strength 10 Per cent Compression Lbs. per Sq.in.			Compressive Strength 20 Per cent Compression Lbs. per Sq.in.		
	Max.	Min.	Ave.	Max.	Min.	Ave.	Max.	Min.	Ave.
1. High grade......	0.280	0.220	0.250	17,710	15,170	16,600	25,080	23,500	24,230
2. High grade......	0.300	0.200	0.250	16,700	16,130	16,400	24,000	23,430	23,640
1. Intermediate....	0.360	0.260	0.300	17,380	15,150	16,000	24,260	22,100	23,030
2. Intermediate....	0.440	0.150	0.310	17,180	15,180	16,130	23,950	22,150	23,150
1. Brass special....	0.430	0.160	0.290	20,910	19,000	20,110	28,580	27,290	28,070
2. Brass special....	0.280	0.160	0.210	18,030	16,190	17,190	25,670	23,680	24,830
1. Prime Western No. 1.........	0.160	0.090	0.130	29,450	27,210	28,270	38,870	38,640	38,770
2. Prime Western No. 1.........	0.200	0.100	0.130	22,780	20,020	20,950	31,390	29,280	29,970
1. Prime Western.. No. 2.........	0.190	0.160	0.180	29,920	27,040	28,700	39,980	38,760	39,490
2. Prime Western No. 2.........	0.220	0.170	0.190	22,080	17,710	20,080	29,990	26,730	28,450
							Max. Load, Lbs.per sq.in.		
Dross	0.070	0.040	0.050	35,880	35,750	35,820	38,530	30,360	34,380

* High strength value explained by finely crystalline structure.

† Low strength value explained by coarsely crystalline structure.

Fig. 312 gives the average stress-deformation curves for the compressive tests of the above series. The effect of the common impurities on the properties of spelters may be summarized as follows:

Lead in moderate quantities tends to make spelter softer in rolling, but weakens the coating formed in galvanizing. In quantities above about 0.7 per cent, it causes castings to crack badly.

Iron hardens spelter and renders it more brittle. An excessive amount of dross is formed in galvanizing.

Cadmium hardens spelter greatly and makes it very brittle. It is therefore particularly undesirable in galvanizing, because it is easily cracked off. Cadmium also tends to cause cracking of castings.

Spelter is largely used as a galvanizing coating; a considerable quantity is rolled into sheet zinc; a further quantity is used in making castings, one variety of which, called "slush castings," are hollow because the metal is poured back into the ladle as soon as a thin layer next the mold has solidified; and a considerable amount is used in combination with copper and other metals in making brass and other alloys.

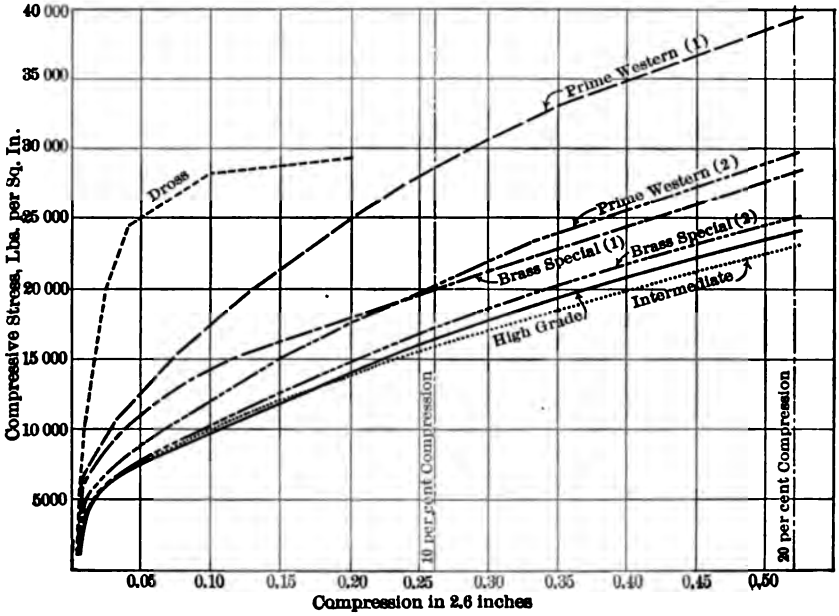

FIG. 312.—Strength of Cast Zinc in Compression. (Rigg and Williams.)

A considerable amount of zinc is also used in the form of zinc dust. A paste of zinc dust is used in the cotton-dyeing industry under the name of "indigo auxiliary." Zinc dust is also used in the making of hydrogen, in galvanizing by various dry methods, in making the electrolyte used for electro-zincing, and in the cyanide treatment of gold and silver ores.

The various zinc pigments made from zinc or zinc ore are much used. Zinc oxide is the most important of these, but leaded zinc oxide, zinc-lead oxide, and lethopone (a mixture of chemically precipitated zinc sulphide and barium sulphate) are used to a certain extent as white pigments for mineral paints.

A large amount of zinc in the form of zinc chloride is also used as a wood preservative.

520. Statistics of Zinc Production. The total production of zinc from primary sources in the United States for the last four years is reported as follows,* the figures being based upon the reports of spelter smelted:

	Short tons
1910	269,184
1911	286,526
1912	339,806
1913	346,676

In addition to the spelter produced from primary sources the following amounts of zinc were derived from secondary sources by the distillation or remelting of old spelter, by the recovery of metallic zinc from brass and other remelted alloys, and by the recovery of zinc in pigment and zinc chloride:

	Short tons
1910	68,998
1911	74,747
1912	94,111
1913	89,528

LEAD

521. General. Commercial Forms of Lead. Lead has been one of the most commonly used metals since the earliest times of which we have any record, and the consumption of the commercial forms of lead is at the present time second to that of only one other non-ferrous metal, namely, copper. Lead occurs in almost every part of the world, usually as a sulphide, but sometimes as oxidized decomposition products of the original sulphide. It usually occurs associated with a small amount of silver, and often its ores contain a notable amount of antimony.

Owing to the common occurrence of the silver and antimony in lead ores, and the further fact that these metals are not removed by the ordinary process of smelting, the output of lead smelters is classed under three heads as follows:

Soft lead is derived by smelting ores which are normally so low in silver that desilverization is not necessary or practical. (Ores derived principally from Missouri and other Mississippi Valley States.)

Desilverized lead is that obtained by special desilverizing treatment of the ordinary argentiferous lead ores.

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* "Mineral Resources," 1913.

Antimonial lead is that which carries an average of about 17 per cent of antimony and about 2 per cent of other metals such as arsenic, copper, etc. It is, of course, an alloy and is sometimes called " type metal," since it is often used in type-founding. It is made from the ore, not from pure metals.

In addition to the forms of metallic lead above listed, lead is used commercially in the form of pigments, and as litharge. The principal forms of lead pigments are *leaded zinc oxide*, which contains from 4 to 20 per cent of lead sulphate, the remainder being zinc oxide with a small portion of zinc sulphate; *zinc lead oxide*, containing 46 to 50 per cent of lead sulphate, 52 to 46 per cent zinc oxide, and a small quantity of zinc sulphate; *sublimed white lead*, which consists of 50 to 53 per cent lead sulphate, 41 to 38 per cent lead oxide, and small proportions of lead sulphide, lead sulphite, and zinc oxide. All of these load pigments are much used as white pigments in the manufacture of mineral paints.

Litharge is lead oxide (PbO), containing 92.83 per cent of lead. It is produced direct from ore, or may be prepared by heating metallic zinc in a current of air. It is used in making flint glass, in glazing pottery, as an oxidizing agent in many processes, and has many other commercial applications.

522. Occurrence in Nature. Ores of Lead. The only important ore of lead is *galena* (PbS), containing 86.57 per cent of lead when pure. It usually contains silver either as silver sulphide or as silver ores, the amount varying from the merest trace up to about 1 per cent (usually less than 0.2 per cent). Galena is found in almost every important country of the world. In the United States the principal deposits are found in Missouri, Idaho, Utah, Colorado, Nevada, Arizona, California, Montana, and New Mexico.

Cerussite ($PbCO_3$), containing 77.52 per cent of lead, *anglesite* ($PbSO_4$), containing 68.3 per cent of lead, and pyromorphite ($Pb_3P_2O_8$), containing 69.5 per cent of lead, are all decomposition products and occur only in the upper portions of deposits of galena.

Only 76.8 per cent of the primary load produced in the United States in 1913 was derived from the lead ores above listed; 11.4 per cent of the total was derived from lead-zinc ores, 8.2 per cent was derived from zinc ores, and 3.6 per cent was derived from all other ores.* In addition, secondary lead, amounting to about 16 per cent of the total quantity of primary lead produced, was derived from old metal, alloys, skimmings, etc.

The average yield of metallic lead per 100 pounds of ore was 5.6 pounds from the lead ores, 4.0 pounds from the lead-zinc ores, and 0.4 pound from the zinc ores.

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* " Mineral Resources," 1913.

523. Extraction of Lead from its Ore. The metallurgical processes involved in the extraction of lead from its ores comprise two main operations, namely, roasting or sintering of the ore, and smelting in the blast furnace, and a number of secondary operations, including treatment of the matte which forms a portion of the products of the blast furnace, the recovery of dust from roasting and smelting furnaces and from matte converters, and the desilverizing of the lead if the silver content is sufficient to justify it.

The methods of roasting lead sulphide ore (galena) in almost universal use at the present day are two forms of a process known as "blast roasting." The process consists essentially in forcing air through finely divided metallic sulphide with the object of partially removing the sulphur, oxidizing the metal, and agglomerating the material in a form suitable for use in the blast furnace.

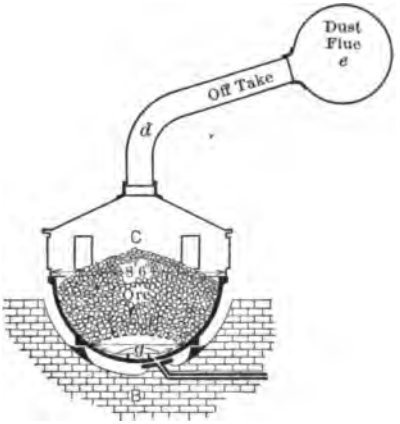

Fig. 313.—Huntington-Heberlein Lead Blast Roasting-pot.

The first of these methods, known as the Huntington-Heberlein process, is an intermittent process carried out in pots which utilize the up-draft principle. Fig. 313 shows the arrangement of the blast roasting-pot. The charge, consisting of a mixture of finely divided galena concentrate and limestone, is placed in the cast-iron kettle *A* which is provided with a perforated cast-iron plate *f* which serves as a grate. A baffle plate *g* distributes the blast which is admitted through the inlet pipe below. The detachable hood *C* is now fitted in place, and the gases driven off, together with the dust which they carry in suspension, are conveyed away by the off-take *d* and the dust flue *e*. The limestone in the charge serves a two-fold purpose: mechanically, it accelerates the speed of roasting by keeping the particles of sulphide separate so that they may become thoroughly oxidized, and, chemically, it acts as a flux which serves to agglomerate the partly roasted ore by the formation of a silicate sinter. The portion of the charge first placed in the kettle is usually hot roasted ore in order to facilitate the starting of the operation, and the process is continued until the sulphur content is reduced to from 4 to 8 per cent. The sinter derived as a result of the operation is broken up before being charged into the blast furnace.

The Dwight-Lloyd sintering machine, Fig. 314, utilizes the down-draft principle (with only a very shallow charge of ore to be penetrated) and is continuous in operation. The charge, in a finely divided state, is fed by a hopper into boxes or trucks called "pallets," which, in combination, form a conveyer, the continuity of which is broken at only one point in the circuit. The pallets are carried on wheels which engage guides by which they are supported. A coal-fired ignition furnace is supported above the trains of pallets, and is so arranged that the flames from the firebox are deflected down upon the ore in each pallet in succession, igniting same just before the pallet comes within the influence of the suction box. While the pallets are passing over the suction box their grate-like bottoms are in direct contact with the planed top of the suction box and all joints between the pallets are closed air tight. A downward draft through the ore to the suction box is maintained by an exhaust fan, and the ore already ignited on top is rapidly sintered. The sinter cake formed is discharged from each pallet in succession as the latter drops into the discharge guides at the end of the circuit. Sprocket wheels now again engage the pallet and gradually return it to the charging position again. The Dwight-Lloyd machine is essentially a sintering machine, and the sulphur removal is not usually carried to the ultimate extent possible in roasting. The machine is used to some extent in agglomerating fine ores, granulating slag, matte, flue dust, etc., for subsequent smelting treatment.

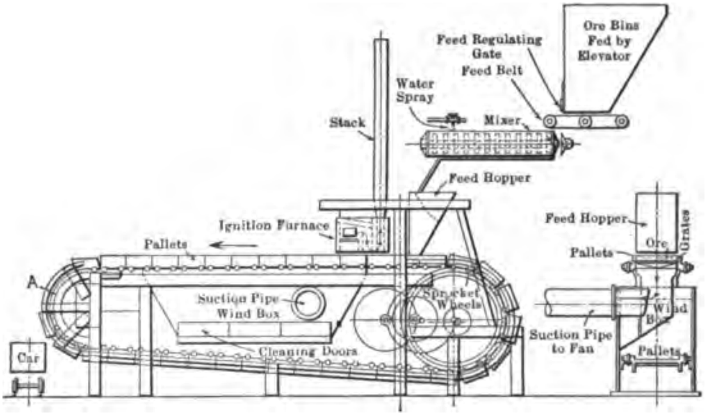

Fig. 314.—Dwight-Lloyd Straight-line Lead Ore Sintering Machine.

The smelting of lead ores is accomplished in rectangular blast furnaces which closely resemble those used in copper smelting. The furnace charge consists of sinter, matte added for remelting or enriching, a small amount of limestone and coke, and a considerable amount of slag. The blast-furnace products are metallic lead, which is tapped from the lead well directly to a molding machine and which may or may not be subsequently refined; matte which contains varying amounts of lead and copper, and which is usually granulated at the furnace, reroasted, and subsequently treated in converters for recovery of lead and copper; and slag which is wasted if clean, but granulated and returned to the furnace if it contains more than 2 or 3 per cent of lead.

The operation of treating the matte for recovery of lead and copper does not differ essentially from the treatment of ordinary copper mattes in the basic converter. Separate lead and copper converters are often necessary.

The operation of the roasting or sintering furnaces, as well as the blast furnaces and converters, result in the carrying off of a great amount of metal in the shape of dust carried in suspension by the gases. The latter are therefore collected and conducted through long cooling and settling flues and finally brought to a "bag house," where the final separation of the solid material is accomplished. A great number of cotton or woolen bags, about 18 inches in diameter and 30 feet long, into which the gases are led and from which dust is collected, are vertically supported in long rows. A fan forces the gases in under light pressure, and mechanical agitation of the bags is usually provided. The material recovered in the bag house sometimes assays as high as 75 per cent lead.

Lead derived by the general methods of operation above described commonly contains varying amounts of arsenic, antimony, tin, zinc, nickel, cobalt, iron, sulphur, copper, and bismuth, in addition to silver, and their removal before marketing the lead is necessary in case they exceed limited proportions. With the exception of copper, bismuth, and silver, all of these impurities are more easily oxidized than is lead, and their removal may therefore be accomplished by an oxidizing fusion. Copper, however, forms with lead an alloy which is less fusible than lead alone, and this separates out when the lead is melted as a scum which may be removed. Silver is usually removed through the agency of zinc by a special process which also removes the last traces of copper, and bismuth can only be removed with great difficulty, but is usually not present in such amounts that it need be taken care of.

Refining, for the sake of removing the impurities other than those specially mentioned above, may be accomplished to a certain degree by skimming the metal in a forehearth after it has cooled to the casting temperature, but if the impurities are present in more than a small amount the refining is commonly done in reverberatory furnaces or in melting pots. Air, sometimes assisted by the introduction of steam or lead oxide, is depended upon to oxidize the impurities. Desilverizaation is usually accomplished by throwing zinc onto the surface of the molten lead, melting the zinc, stirring the whole thoroughly, allowing the bath to cool, and removing the scum of lead-zinc silver alloys which forms on the surface. This scum not only contains all the silver originally present, but also removes the last vestige of copper. From this mixture of alloys the zinc can be separated by distillation and the lead is subsequently separated from the silver by an oxidizing melting in a reverberatory furnace, the lead oxide formed being withdrawn in a molten condition while the silver remains behind.

524. Properties and Uses of Lead. The commercial uses of lead are of such a nature that the only physical properties commonly taken account of are its hardness, its malleability, and its resistance to corrosion after a thin oxide film has formed on the surface. Antimony, arsenic, copper, and zinc harden lead, when present to any considerable extent, but, with the exception of antimony, they are seldom present in refined lead to an extent which renders their effect appreciable. Antimonial lead or " hard lead " is much used as type metal, bearing metal, and for shot and bullets. Lead used for rolling into sheet metal for pipes must, however, be as free as possible from antimony and arsenic as well as metallic sulphides or other hardening elements.

Lead is much used in the shape of pipe (formed by forcing molten lead through a die, against which it chills, by means of an hydraulic press), and in the form of sheet lead, used in the linings of vats, tanks, chambers, etc., for chemical manufacturing processes, and for flushings, gutters, and other roofing purposes. (Sheet lead is rolled cold after casting in the form of a comparatively thin sheet.) Tea lead is a form of very thin sheet lead, so called because used primarily in lining tea-chests. The character and uses of lead pigments and litharge have been indicated above.

525. Statistics of Lead Production. The total production of lead in the United States for the last four years is reported as follows * (quantities are expressed in short tons):

Year.	Primary Lead.				Secondary Lead.		
	Antimonial Lead.	Desilverized Soft Lead.	Other Soft Lead.	Total Soft Lead.	Pig Lead.	Lead in Alloys.	Total.
1910	14,069	328,954	141,318	470,272	29,492	25,930	55,422
1911	14,078	331,032	155,947	486,979	27,389	26,895	54,284
1912	13,552	339,646	141,248	480,894	30,266	36,902	67,168
1913	16,665	330,593	131,867	462,460	33,104	39,730	72,834

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* " Mineral Resources," 1913.

TIN

526. General. Commercial Forms of Tin. Tin is used quite extensively in the form of sheet tin, and as tinfoil, but has almost no other commercial application except as a constituent of many valuable alloys. It is one of the few important metals which is found abundantly in other parts of the world which is not also abundant in the United States. The principal sources of tin are the Federated Malay States in the East Indies (referred to as the Straits or Straits Settlements), England (Cornwall and Devon), Australia, and Bolivia.

527. Occurrence in Nature. Tin Ore. The only ore of tin which is used for extraction of the metal is *tin stone* or *cassiterite* (SnO_2), containing 78.6 per cent of the metal. It occurs both in lodes or veins, when it is called *lode tin,* and in secondary deposits of water-worn particles, called alluvial deposits of *stream tin.* By far the greatest portion of the world's tin supply is derived from the alluvial deposits in the Federated Malay States. Bolivia ranks next, being the greatest producer of lode tin. Australia produces considerable amounts of both alluvial and lode tin, and, in England, where alluvial deposits had been worked from the time of the Phœnicians, only lode tin is now available in the old workings. In the United States only relatively small amounts of tin are mined, the principal source being Alaska.

528. Extraction of Tin from its Ores. The extraction of tin from its ore involves the mechanical, or combined mechanical, thermal, and chemical, concentration of the ore, reduction by smelting with charcoal or coke in shaft furnaces or reverberatory furnaces, and refining of the crude tin derived by smelting.

When the ore is in the form of alluvial deposits a large proportion of the earthy material, quartz, silicates, and metallic oxide impurities may be removed by mechanical separation methods. Lode ores usually require an oxidizing roasting in reverberatory furnaces. Sulphur and arsenic are thus expelled and the metals with which they were combined are converted into oxides. These metallic oxides are subsequently removed by washing, a second roasting and washing treatment being sometimes required when the arsenic content of the ore is very high. When copper and bismuth are present, their oxides formed by roasting are removed by leaching with dilute sulphuric or hydrochloric acid before further washing.

Two-thirds of the tin produced is smelted in small shaft furnaces in which wood charcoal is used as fuel and reducing agent. Finely divided ores require the addition of a loosening agent (slags), in order to make smelting possible, and the increase in the amount of slag produced thereby increases the amount of tin lost in the slag. The furnace must be worked with a low depth of charge and low blast pressure in order to prevent excessive loss by volatilization and by the carrying off of fine dust by the blast. Dust chambers are usually provided to collect this ore dust and volatilized tin. In order that the tin may be subjected to the oxidizing blast as little as possible, the furnace is usually worked with an open tap hole, and the separation of the slag and tin is effected in a forehearth.

The reverberatory furnace is able to smelt fine ore without the addition of a slag, but coal for reduction purposes is used in addition to that burned as fuel in the separate firebox. The tin produced in the reverberatory furnace may be purer than that from the shaft furnace, and little loss is occasioned by volatilization or as flue dust. More tin is lost in the slag, however.

The slags, skimmings, furnace accretions, etc., are treated by processes of smelting with a lime flux or smelting with scrap iron, the lime or the iron serving to reduce the oxide of tin.

The crude tin obtained by the above processes must usually be refined in order to remove its impurities—iron, copper, lead, antimony, and arsenic. The most common refining treatment is simply a *liquation* process, the pure tin being melted out on a hearth and allowed to escape while the less fusible alloys of the impurities remain behind as liquation dross. Sometimes liquation is followed by *boiling* or *tossing*. The *boiling* process consists in maintaining the tin in a molten condition in a pot, the metal being agitated by the gases and vapor given off when a bundle of green twigs is thrust into the bath. This treatment brings every portion of the metal in contact with the air and the more easily oxidized metals are oxidized and form a scum on top which is skimmed off. When there is no longer any scum on the metal it is allowed to cool, in order that the heavy metals (principally copper and iron) may settle to the bottom, after which the metal is ladled into molds. The upper portion of the metal in the pot is purest, the lower layers are of intermediate quality, and the portion at the bottom is usually liquated and boiled again. *Tossing* differs from boiling only in that a workman continually takes up a ladleful of metal and pours it back into the melting pot from a considerable height, thus facilitating oxidation.

529. Properties and Uses of Tin. The properties of tin of commercial importance are its extreme malleability at ordinary temperatures, and its high resistance to corrosion when pure. A very large portion of the world's production is cold rolled into sheet tin and used in the manufacture of cans, as roofing material, etc. A smaller proportion is used as a coating on sheet iron or steel, or as tinfoil. When heated above atmospheric temperatures it becomes brittle, until at 200° C., it can be powdered by hammering. Iron in considerable amounts makes tin hard and brittle and less rust resistive. Arsenic, antimony, and bismuth, in amounts exceeding about 0.05 per cent, lower its strength considerably, and copper and lead (1 to 2 per cent) increase its hardness and strength, but render it less malleable.

530. Statistics of Tin Production and Consumption. The production of primary tin in the United States is a negligible amount when compared with our consumption of tin, which in 1913 amounted to 40.8 per cent of the world's production. From 5000 to 6000 tons of secondary tin is annually recovered from scrap tin, however.

The consumption of tin, excluding that contained in imported ore, tin foil, etc., is reported as follows: *

	Short tons
1910	52,528
1911	53,527
1912	58,016
1913	53,315

ALUMINUM

531. General. Commercial Forms of Aluminum. The history of aluminum as a metal of commercial importance is very brief, the first practicable processes for the production of metallic aluminum having been developed since 1886. Prior to that time the metal was merely a chemical curiosity, but in the years that have followed the discovery of electrolytic extraction methods it has assumed a position of great importance among non-ferrous metals and now has a multitude of important every-day applications in the arts and industries. It is recommended particularly by its lightness (sp.gr. = 2.60–2.74) combined with a high degree of strength, great ductility, and malleability, non-corrosiveness, and immunity from acid attack.

Aside from its very common use as rolled, pressed, drawn, or cast metal, metallic aluminum is considerably used in the form of aluminum foil, like tinfoil, and as powdered aluminum which is used extensively as a paint pigment, in explosives, and in lithographing and in printing.

532. Occurrence in Nature. With the exception of oxygen and silicon, aluminum is the most abundant element on the globe; yet there are few minerals which have been successfully used for its extraction. The most important are *bauxite* and *cryolite*, while rocks containing aluminum sulphate, kaolin, and clay are of much less importance. Whatever

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* "Mineral Industries," 1913.

the original source of the material, it is converted into alumina (Al_2O_3), before the metal is extracted.

Bauxite is a mixture of alumic and ferric hydrates containing widely varying amounts of alumina, ferric oxide, silica, calcium and magnesium carbonates, water, etc. Important deposits occur in France, Germany, Ireland, Italy, Australia, and in the United States in Arkansas, Georgia, and Tennessee. Most bauxites carry from 40 to 55 per cent alumina.

Cryolite is a double fluoride of sodium and aluminum, represented by the formula Al_2F_6+6NaF, and containing, when pure, 13.07 per cent aluminum.

533. Extraction of Aluminum. The only methods of extraction of aluminum of commercial importance consist in the electrolysis of comparatively pure alumina dissolved in a bath of molten cryolite. Alumina for the purposes of electrolysis is at present principally made from bauxite, but may be prepared by treating silicious bauxite, kaolin, or clay with sulphuric acid, and subsequently driving off the sulphuric acid from the aluminum sulphate produced, by ignition. Bauxite is treated with a soda solution, and the alumina is extracted as sodium aluminate. The alumina may be precipitated from the solution as hydroxide by carbon dioxide, and subsequently washed, filtered, and dehydrated by heating, or it may be precipitated as hydroxide by stirring the solution with pure aluminum hydroxide.

The general features of the production of aluminum by the electrolysis of alumina dissolved in molten cryolite are as follows:

A bath is formed by the melting of cryolite in a small pot which is built of plate iron and provided with a thick carbon bottom lining. The construction of one form of electrolytic alumina reducing pot is shown in a general way by Fig. 315. Carbon anodes are suspended at frequent intervals in such a manner that they project into the bath, but do not touch the carbon cathode which forms the bottom lining of the pot. The cathode carbon is in contact with the iron shell and the latter forms the negative pole. Provision is made for raising and lowering the anode carbons.

In operation, alumina in a finely divided state is spread over the bath of molten cryolite and stirred in. Thereupon it becomes melted by the heat developed by the resistance of the bath to the passage of current, and dissolves in the bath. Electrolysis now begins immediately, the alumina being decomposed into aluminum and oxygen. The aluminum migrates to the cathode, where it is precipitated, and the oxygen at the anode forms carbon monoxide gas. As the bath becomes impoverished, fresh alumina and cryolite are added from time to time. The aluminum collects on the bottom and is ladled or tapped out at frequent intervals. In large works a number of baths are arranged in series, and operation is continuous.

The details of modern methods of electrolytic reduction of alumina have not been permitted to become generally known, nor is information available concerning the detail design of aluminum extracting equipment. According to Börchers * the temperature of the bath is 750° C., the tension is 7.5 volts, and the current density 6000 amperes per square yard of bath area, when the horizontal section of molten material is 2 feet 6 inches by 5 feet, and the depth of bath 6 inches. The early baths were completely lined with carbon, but it was later found that electrolyte which solidifies on the side walls forms all the protection required by the iron plates, the latter being cooled by circulating air.

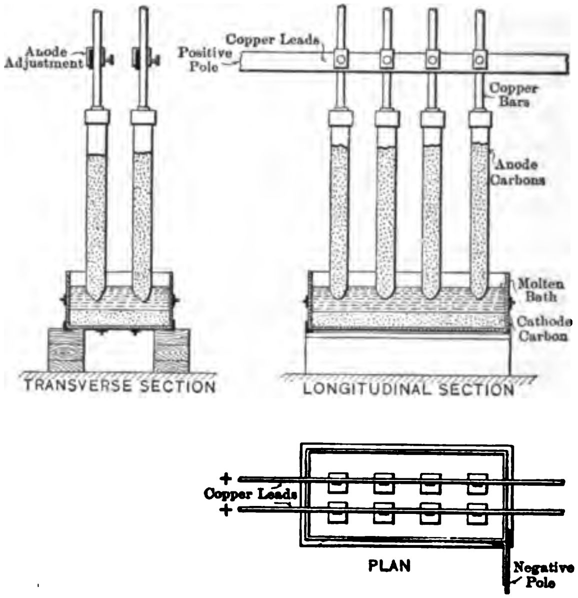

FIG. 315.—Bath for Electrolysis of Solutions of Alumina.

The metal derived as the product of the above operation is commercial aluminum, and is usually about 98 to 99.5 per cent pure. Special grades are obtainable, containing as much as 99.9 per cent aluminum, and some second grade metal is sold which contains not over 95 or 96 per cent aluminum. The principal impurities are silicon and iron.

534. Properties and Uses of Aluminum. The general properties of commercial aluminum are indicated by the following table. The

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* "Electrometallurgie," 1902, p. 154.

minimum values apply to metal in an annealed condition, and the maximum values to metal that has been cold worked to an extreme degree by forging, cold rolling, or drawing, without subsequent annealing.

	Tension.			Compression.		Modulus of Elasticity. Lbs. per Sq.in.
	Elastic Limit. Lbs. per Sq.in.	Ultimate Strength. Lbs. per Sq.in.	Reduction of Area. Per cent.	Elastic Limit. Lbs. per Sq.in.	Ultimate Strength. Lbs. per Sq.in.	
Castings.........	6,000 to 10,000	15,000 to 25,000	10 to 20	3000 to 5000	10,000 to 15,000	8,000,000 to 10,000,000
Rolled sheets and Bars..........	10,000 to 25,000	20,000 to 35,000	20 to 40	2000 to 6000	9,000 to 12,000	12,000,000 to 15,000,000
Cold drawn wire..	15,000 to 35,000	25,000 to 55,000	40 to 70	....	....	15,000,000 to 20,000,000

The very marked effect of cold working in increasing the strength and improving the elastic properties of the metal is exhibited by the above maximum values. The ductility is very considerable, and it works well, at temperatures below about 200° C., in rolling or forging. Cold working hardens aluminum excessively, and in wire drawing the metal must be frequently annealed to restore ductility.

The low electrical resistance of aluminum is one of its most valuable properties, since a relatively high conductivity, combined with its lightness and strength, makes it especially well adapted for use on long-span transmission lines. The conductivity of 98.5 per cent pure aluminum is about 55 per cent of that of copper, and the specially pure grades rank somwhat higher, the conductivity of 99.9 per cent pure aluminum being about 65 per cent of that of copper.

Aside from the electrical uses of metallic aluminum immense quantities are used in the manufacture of many articles of every-day domestic use and in many industries where tanks, cooking vats, etc., which must be heat-conductive, non-corrosive, and non-poisonous, are used. For these purposes the metal is either cast or rolled, and many articles are finished in a press. A further quantity of aluminum is finished in the form of seamless tubing which has many important applications.

Aluminum may be used for casting purposes where lightness and softness are required rather than hardness and strength. Most of the aluminum used for these purposes, however, is slightly alloyed with other metals which harden it and materially increase its strength. Much of the rolled and drawn aluminum is also slightly alloyed, with an improvement in strength and hardness.

535. Statistics of Production and Consumption of Aluminum. The production and consumption of aluminum in the United States are reported as follows; all figures are given in pounds:

	1910	1911	1912	1913
Production*.......	....	....	32,990,000	49,601,500
Consumption†.....	47,734,000	46,125,000‡	65,607,000‡	72,379,090‡

* As reported by the Metallgesellschaft, Frankfurt am Main.

† "Mineral Resources," 1913.

‡ Leaf aluminum, table, kitchen, and hospital utensils, and other miscellaneous manufactures of aluminum are not included.

NICKEL

536. General. Commercial Forms of Nickel. Nickel is by far the least important of the metals classified above as metals of primary importance. The world's production of nickel amounts to less than 3 per cent by weight of that of either lead or copper, and amounts to only 3.5 per cent of that of zinc. Most of the metallic nickel produced is derived from pyritic or silicate ores, or as a by-product of the refining of blister copper.

Metallic nickel has very few commercial applications. A limited amount is incorporated with iron as ferro-nickel and used in the making of nickel steel; a further quantity is used in alloys of non-ferrous metals; and a small quantity is used as anode plates for electrolytic nickel plating of various metals. In the form of the double sulphate with ammonium ($Ni(NH_4)_2(SO_4)_2$), it is also used as the electrolyte in nickel plating.

537. Occurrence in Nature. Ores of Nickel. Nickel is a constituent of many minerals, sometimes as the principal metallic element, but more frequently as a secondary element only extracted because smelting is justified by the presence of other metals, such as copper, in the natural mixture of minerals which includes nickel compounds. The only minerals from which nickel is obtained to any considerable extent are *nickel pyrites* and the silicate *garnierite.*

Nickel pyrites or *millerite* (NiS) occurs in large quantities in the Sudbury district of Ontario, Canada, and is found in a few other unimportant deposits. It contains 64.5 per cent of nickel and is almost invariably associated with iron and copper pyrites. The Sudbury ores average about 3 per cent of nickel.

Garnierite is a nickel-magnesium silicate of variable composition usually containing from 9 to 17 per cent of nickel oxide, with varying amounts of silicon, magnesia, ferric oxide, etc. The principal source of garnierite is on the island of New Caledonia. These ores usually contain about 7 or 8 per cent of nickel.

538. Extraction of Nickel from its Ores. The methods of extraction of nickel from sulphur compounds on the one hand, and the extraction from silicates on the other hand, differ in certain respects, and will therefore be briefly considered separately.

The smelting of sulphur compounds, after removal of gangue, involves principally the separation of nickel from sulphur and from iron, and in most cases from copper also. The first operation consists in roasting the pyrite ore, the methods and equipment used differing in no respect from those used in treating other classes of sulphide ores. The object of roasting is to remove sulphur until only enough remains to combine with nickel, copper, and a portion of the iron, during the smelting operation which follows. Most of the iron becomes oxidized during roasting and the sulphides of the nickel, copper, and iron are in part converted into sulphates.

The second step in the process is the smelting of the roasted ore in a blast furnace with carbon and silicious matter. All of the iron which has been previously oxidized passes into the slag, while the residue of undecomposed iron sulphide forms a matte containing all of the nickel and copper sulphides. Any oxides of nickel and copper react with iron sulphide in the blast furnace, decomposing and slagging the latter as iron silicate (with the assistance of the silica), and themselves becoming sulphides. The smelting furnace used resembles the copper blast furnace and the resultant coarse matte should contain 15 to 25 per cent of nickel unless the ore is very lean. In the latter case the coarse matte is enriched by a repetition of the roasting and smelting process. Complete separation of the iron cannot be effected in the smelting operation because of the loss of nickel in the slag that would result, and the next step in the operation is therefore the removal of the iron sulphide by an oxidizing fusion, the iron being converted into ferrous oxide, which combines with silica and is slagged off. This operation is accomplished in a converter, and the removal of iron is complete. Any nickel or copper which is oxidized reacts with ferrous sulphide, forming ferrous oxide (which is slagged), and sulphides of nickel or copper. It is not possible, however, to separate metallic nickel as copper is separated, by continuing the blow. The slag produced usually contains notable amounts of nickel and copper and is therefore returned to the smelter. The refined matte produced usually contains from 30 to 40 per cent of nickel, and any amount of copper up to, or slightly exceeding, the amount of nickel. Both are in the sulphide form.

The derivation of metallic nickel and copper from the refined matte is accomplished by a number of methods, the details of which are not generally known. The Orford process consists in removing the copper and the little residual iron by repeatedly smelting it in small blast furnaces with sodium sulphate (Glauber salt) and carbon (coal). The copper forms a complex sulphide of sodium, copper, and iron, and nickel sulphide remains behind. This is roasted to nickel oxide, which is finally reduced by carbon (charcoal) in crucibles. A considerable proportion of the nickel oxide is marketed as such, since it may be used in this form for alloying purposes.

The Mond process consists in roasting the matte, extracting part of the copper with sulphuric acid and reducing by smelting to a nickel-copper alloy. By subjecting this to the action of carbon monoxide at the proper temperature, the nickel is converted into the gaseous nickel carbonyl, and the latter is finally decomposed by heat into metallic nickel and carbon monoxide.

Electrolytic methods of refinement have also been used successfully in treating refined matte. The latter is roasted, smelted for copper-nickel alloy, and the latter electrolyzed.

The extraction of nickel from the silicate differs from the methods employed in treating sulphur compounds principally in that the initial smelting of the ore is done in a blast furnace with the addition of sulphur compounds, in order to produce a matte containing the nickel in the form of sulphide.

The ore is mixed with calcium sulphide (derived from the Leblanc soda process), or with gypsum, and with coal or coke. The mixture is crushed to powder, pressed into briquettes, and charged into the blast furnace. If gypsum is used it is reduced to calcium sulphide by the carbon in the furnace, and the calcium sulphide is decomposed by the nickel silicate of the garnierite, nickel sulphide and calcium silicate being formed. The resultant matte is rather richer in nickel sulphide than that obtained in smelting sulphur compounds, and the subsequent separation of the iron sulphide, the refinement of the second matte, and the final derivation of metallic nickel is accomplished by practically the same methods that are used in treating matte from sulphur compounds.

539. The Properties and Uses of Nickel. The most important property of nickel, aside from the advantages which it may confer upon steel or non-ferrous metals with which it is alloyed, is its non-corrosiveness. On this account and because of its silvery appearance, one of the commonest commercial applications of metallic nickel is in plating iron, steel or other metals. Its mechanical properties are excellent, sometimes equaling those of medium-carbon steel, but it is too rare and expensive for general use. It is quite ductile, and fairly malleable, but is rendered brittle and incapable of being rolled by not more than 0.1 per cent of arsenic or sulphur. Most of the other impurities common to commercial nickel are not injurious to its properties, and some are beneficial in limited amounts.

The principal uses of nickel have been indicated above in Art. 536.

540. Statistics of Nickel Production and Consumption. No nickel is produced in the United States except as a by-product of the refining of blister copper, and by refining matte, nickel oxide, and copper-nickel alloys which are imported. The United States production of nickel by the refining of blister copper amounted to about 480,000 pounds in 1913, and the importations of nickel in the form of nickel, matte, nickel oxide, and copper-nickel alloys (from Canada for the most part, a small amount coming from New Caledonia) in the last four years are reported as follows: *

NICKEL CONTENT IN POUNDS OF IMPORTATIONS OF NICKEL IN VARIOUS FORMS

1910	1911	1912	1913
32,373,251	29,829,268	46,317,078	47,446,520

THE NON-FERROUS ALLOYS

GENERAL

541. The Non-ferrous Alloys in General. The study of metallic alloys is a very complex one, not only on account of the great number of combinations of two or more metals which have been found to possess valuable attributes, but also because of the inherent complexity of the problem of the interaction of metals combined in a state of fusion. True alloys of metals are never mechanical mixtures of the constituents, but are either (*a*) solid solutions of the metals, (*b*) solid solutions of a chemical compound of the metals in the metal which is in excess, or (*c*) mixtures of such solutions with definite substances which have crystallized out during cooling. The composition, constitution, and structure of many alloys may therefore vary widely, and the physical characteristics likewise vary, and can be predicated upon a knowledge of the properties of the constituent metals to only a slight extent.

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* "Mineral Resources," 1913.

Many important investigations of the more important alloys, or groups of alloys, have been made in recent years, and no small portion of our present knowledge of the subject has been gained through the application of modern methods of research in physical chemistry, by the use of microscopic methods, and by study of the phenomena of fusion and solidification.

These studies have an important bearing upon the study of purely physical properties which alone possesses a direct interest for the engineer or artisan. In the present discussion of the subject, however, no effort will be made to cover anything more than the composition, physical properties, and uses of the alloys which possess a distinct commercial importance.

COPPER-TIN ALLOYS. BRONZES

542. Ordinary Bronzes. Alloys of copper and tin are among the most useful of all the non-ferrous alloys, and have been known and used since prehistoric times. The influence of tin upon the properties of copper is that of a pronounced hardener and strengthener, so long as a limiting percentage of 20 or 25 per cent is not exceeded. The range of composition of ordinary commercial bronzes is not wide, all of the important ones containing 80 per cent of copper or more. An immense amount of information concerning the properties of bronzes has been collected.

Fig. 316 presents a summary of the mechanical properties of a series of bronzes tested by the Committee on Alloys of the United States Board to Test Iron, Steel, and Other Metals.* The work was done under the direct supervision of Professor Robert H. Thurston. In spite of the exercise of the greatest care in conducting the investigation, the properties of the individual specimens of the 29 alloys tested varied widely, and the comparatively smooth curves of Fig. 316 simply average up the results in a general way. All of the specimens used in this series of tests were of cast bronze, the transverse test specimens being the original cast bars 1 inch square in section and centrally loaded on a span of 22 inches. The tensile specimens were turned from the ends of the transverse test specimens, the reduced portion being 6 inches long and 0.798 inch in diameter (0.5 sq.in. in area), and deformations were measured on a 5-inch gauged length. The compressive specimens were cylinders 2 inches long and 0.625 inch in diameter turned from the ends of the tensile specimens.

The bronzes exhibiting the greatest tensile strength and bending strength, and the highest yield point, are those containing more than 80

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* Report of U. S. Board to Test Iron, Steel, and other Metals, 1881.

per cent of copper. The compressive strength appears to increase with decrease in copper content until an alloy containing about 75 per cent

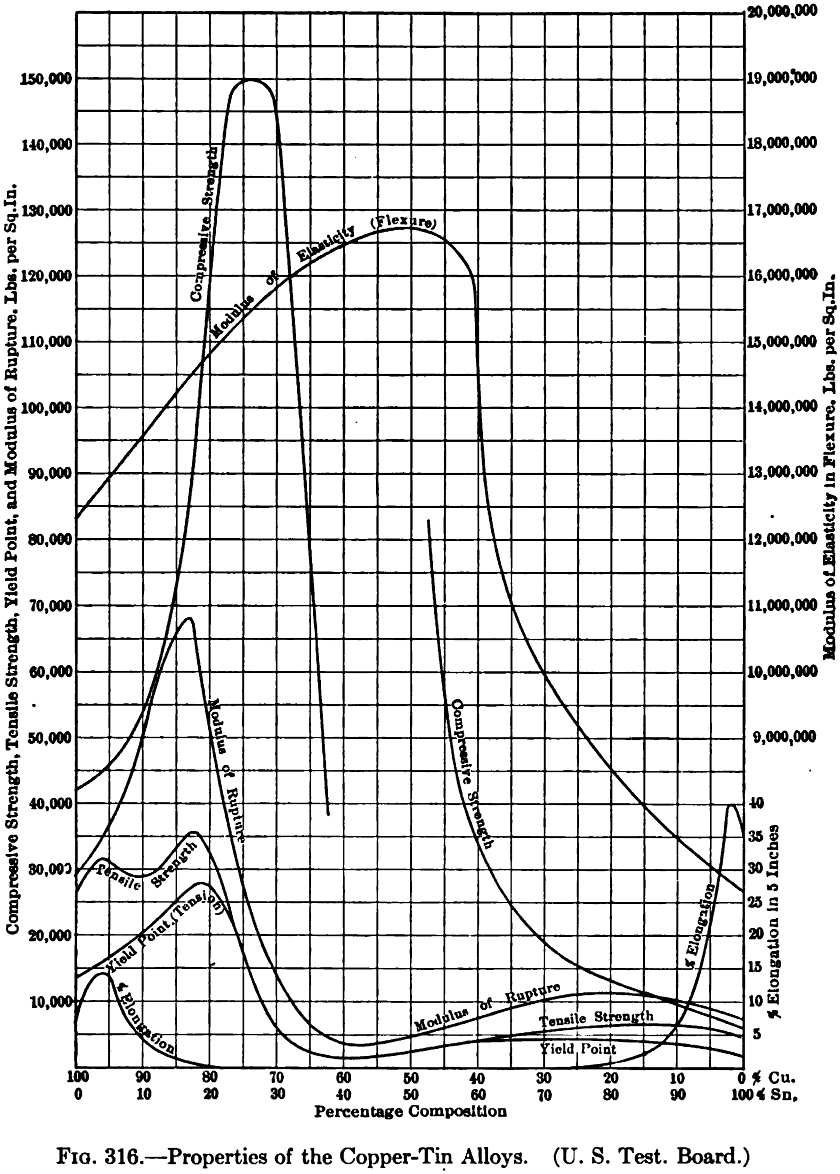

FIG. 316.—Properties of the Copper-Tin Alloys. (U. S. Test. Board.)

of copper and 25 per cent of tin is passed. Beyond these limits the strength decreases rapidly in all cases with further additions of tin. The stiffness appears to increase until a 50 per cent tin alloy is reached, but the ductility reaches its maximum with only about 4 per cent of tin, and is entirely lacking with more than 25 per cent of the latter, until alloys are reached which begin to approach pure tin in properties, when the great ductility of the latter comes to be characteristic of the high-tin alloys. All of the alloys containing between 25 and 75 per cent of tin are extremely brittle and weak, and those containing more than 75 per cent of tin are weak and soft.

The strength and ductility of bronzes are considerably affected by heat treatment. M. Guillet * found that, with bronzes containing over 92 per cent of copper, quenching between 400° and 600° C. slightly increases the strength and ductility. With less than 92 per cent of copper, both strength and ductility increase decidedly as soon as the quenching temperature exceeds 500° C. The maximum strength of all alloys was found to be reached by quenching at about 600° C., the beneficial effect becoming more marked as the copper content is reduced.

The most commonly used types of ordinary bronzes are the following (it will be noted that a number of these alloys classed as ordinary bronzes sometimes contain small amounts of zinc, lead, etc.):

Machinery bronzes are used principally as hard bearing metal, as metal for cut gears, and for valves, bushings, stuffing boxes, piston rings, steam whistles, plumbing fixtures, etc. The average machinery bronze contains from 81 to 87 per cent of copper, and 19 to 13 per cent of tin. Most gear bronzes contain phosphorus or manganese or both, and will therefore be considered under the head of "special bronzes." Frequently bearing bronzes contain from 2 to 4 per cent of zinc, as do also many of the bronzes used for the various machine parts above listed. Locomotive bronzes and piston rings may contain as much as 8 or 9 per cent of zinc. (The properties of the ternary bronzes are considered in the following article.)

Gun metal usually contains from 88 to 92 per cent of copper and 12 to 8 per cent of tin. It is one of the strongest of all the bronzes. It was at one time commonly used for casting guns, but has now been entirely replaced by steel in ordnance concentration and is used only as a material for strong castings. It is not infrequently alloyed with small percenages of zinc or even lead.

Bell metal usually contains from 75 to 80 per cent of copper and 25 to 20 per cent of tin. It is largely used for bell founding, because of its resonance, but is hard and brittle. (A number of brasses and ternary alloys are also used in bell founding.) Small amounts of zinc or lead

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* "Étude Industrielle des Alliages Metalliques," 1906.

are occasionally used in bell metal, and silver is sometimes added with the idea that the tone is improved.

Speculum metal usually contains 65 to 70 per cent of copper and 35 to 30 per cent of tin. Before the present state of the art of manufacturing silvered glass reflectors was attained it was always used for the specula of reflecting telescopes. Its value is due to the fact that it is extremely hard, and therefore takes a smooth polish, and possesses a silvery white color.

Statuary bronzes usually contain from 90 to 78 per cent of copper, 2 to 10 per cent of tin, and any amount of zinc up to 10 or 15 per cent. They often contain more zinc than tin, and therefore ought to be classed as special bronzes or brasses.

Coin or *medal bronzes* contain from 90 to 97 per cent of copper and 10 to 3 per cent of tin. Occasionally very small amounts of zinc or lead are added.

543. Special Bronzes. *Copper-tin-zinc Bronzes.* The copper-tin-zinc alloys are among the most valuable and commonly used of all the bronzes. The range of composition of the commercial bronzes of this class is from 50 to 95 per cent of copper, 1 to 15 per cent of tin, and 5 to 50 per cent of zinc.

The tensile strength of copper-tin-zinc alloys is exhibited by the diagram of Fig. 317, which is based upon the report of the U. S. Board to Test Iron, Steel, and Other Alloys above referred to. The triaxial diagram used in this instance is based upon the geometrical principle that the sum of the normals from any point in an equilateral triangle upon the sides is equal to the altitude of the triangle. The altitude is made to represent 100 per cent of any of the constituents. Thus the altitude measured to one vertex from the opposite side represents 100 per cent of copper, that to the second vertex 100 per cent of tin, and that to the third vertex 100 per cent of zinc. Each side of the triangle represents zero content of the constituent represented by the opposite vertex, and the distance of a point within the triangle to any side, expressed as a proportion of the altitude, expresses the percentage of the constituent represented by the vertex opposite the side chosen. Any point in the diagram therefore represents a certain definite alloy or mixture of three constituents. Thus point A on the diagram represents an alloy containing 13 per cent of copper, 57 per cent of tin, and 30 per cent of zinc. Each alloy tested is therefore represented by some one point on the diagram, and when all such points have been plotted and marked with the figures representing the particular property under investigation (tensile strength in this case), lines or contours may be drawn connecting points representing alloys possessing the property in question to an equal degree, and the result is such a diagram as is here presented.

It is evident at a glance that all of the alloys possessing sufficient strength to be considered of any value are those containing more than 50 per cent of copper, less than 20 per cent of tin, and less than 50 per cent of zinc. The strongest alloys contain nearly 60 per cent of copper, 1 to 2 per cent of tin, and nearly 40 per cent of zinc. The diagram does not show the ductility of the various alloys, but the data of the original tests reveal the fact that the most ductile alloys are in the upper portion of the field comprised within the 30,000-pound-per-square-inch contour line. All of the alloys containing more than 10 to 20 per cent of tin (the higher, the lower the zinc content), are extremely brittle and fragile, and are altogether worthless. The alloys having a tensile strength of from 30,000 to 40,000 pounds per square inch are the most generally useful ones, since they are comparatively tough and are very ductile, showing from 10 to 30 per cent elongation at rupture in tension.

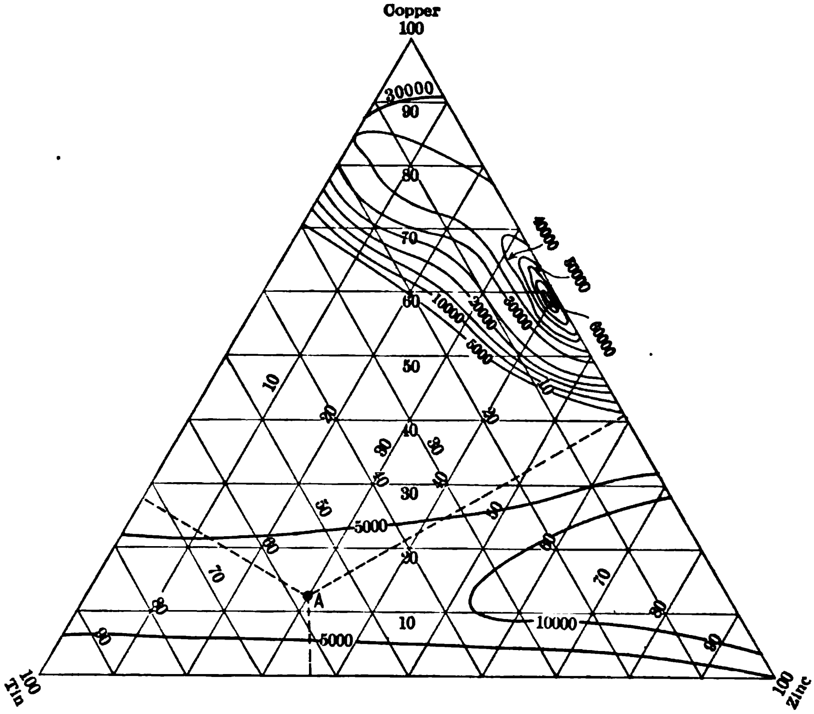

FIG. 317.—Tensile Strength of Copper-Tin-Zinc Alloys. (Compiled by J. B. Johnson from Report of U. S. Test. Board.)

The character and uses of the most important copper-tin-zinc bronzes have been indicated above under the head of machinery bronzes.

Copper-tin-lead Bronzes. Lead is not infrequently added to bronzes used for bearings, for the purpose of increasing the plasticity just enough to allow the metal to adapt itself to the running surface so that the bearing is uniform over the whole surface. The addition of from 10 to 40 per cent of lead to a bronze containing 5 to 10 per cent of tin cuts down the wear on the bearing very materially without increasing the friction more than very slightly. The degree of softness desirable in a bearing bronze is dependent upon the conditions of service, and the lead content and tin content are varied accordingly. In general, the lower the content of tin, the higher the content of lead desirable. An alloy of this class commonly used for railway service and other purposes is known as "plastic bronze." It contains 65 per cent of copper, 30 per cent of lead, and 5 per cent of tin.

Phosphor Bronze. The addition of very small percentages of phosphorus to any bronze has a remarkable effect upon its properties. The tensile strength is considerably increased, and the elastic limit and endurance under repetition of stress are very greatly increased. Phosphorus added in small amounts acts principally as a deoxidizer, and the marked improvement in the properties of the bronze is principally due to the elimination of copper oxide. In slightly larger quantities the phosphorus combines with copper to form a compound which greatly hardens the bronze.

Phosphor bronzes intended for use as engine parts, valve metal, etc., usually show only traces of phosphorus and contain about 7 per cent of tin. Phosphor bronze for gears is harder, owing to the presence of 8 to 12 per cent of tin, and phosphorus varying from mere traces up to a maximum of about 0.2 per cent. Bearing bronzes most commonly contain 8 to 10 per cent of tin and from 0.2 to about 0.9 per cent of phosphorus. Certain bearing bronzes, particularly those for railway service, contain about 10 per cent of lead in addition to 10 per cent of tin and about 0.3 per cent of phosphorus. These bronzes excel any other class of bearing metal in resistance to wear under severe conditions, and in addition possess a very low coefficient of friction.

Phosphor bronzes of proper composition may be rolled or drawn into wire, and when so fabricated exhibit about the same tensile properties as does medium structural steel. Working cold has the same effect that it has in the case of steel, the strength, and especially the elastic limit, being raised to a marked extent. All of the phosphor bronzes are remarkably resistant to corrosion, and are much used on subaqueous construction and in other situations on this account.

Manganese Bronze. The so-called manganese bronze, which is now commonly used for a great variety of purposes, is really a special brass, since it contains very large amounts of zinc and little or no tin. This class of alloys will therefore be considered under the head of special brasses.

Silicon Bronze. Silicon added to ordinary bronzes has about the same effect as similar additions of phosphorus. Its principal action added in small quantities, is that of a deoxidizer, and it has about the same effect upon the properties as has phosphorus, the strength and especially the elastic limit being raised, although only a trace of silicon may appear in the finished bronze.

In one important respect silicon differs in its effect from phosphorus. The latter, even in very small amounts, is very detrimental to electrical conductivity, but silicon is not. In consequence, silicon bronze is a much better conductor than phosphor bronze, and is considerably used for telephone wires, etc.

Aside from its electrical conductivity, silicon bronze possesses most of the valuable properties of phosphor bronze, and is used for similar purposes where a strong, hard, and non-corrosive alloy is desired in the form of castings, rolled sections or sheets, or drawn wire.

Aluminum Bronze. The alloy commonly known as aluminum bronze contains no tin, but is simply an alloy of copper and aluminum, and so is not really a bronze at all. Its character and properties will be considered under the head of binary alloys of copper other than bronzes and brasses.

Vanadium Bronze. Vanadium has occasionally been added to bronzes in very small amounts with remarkably beneficial effects upon properties. These bronzes have not become commonly known or used, however.

Nickel bronzes are for the most part quaternary alloys containing about 30 to 40 per cent of lead, 5 per cent of tin, and 1 per cent of nickel, the balance being copper. The nickel serves particularly to prevent the separation out of lead during solidification, and produces a homogeneous alloy containing more lead than can ordinarily be used without danger of segregation. This alloy is an important bearing bronze and is considerably used in machine construction and for railway service.

COPPER-ZINC ALLOYS. BRASSES

544. Ordinary Brasses. Alloys of copper and zinc, with or without addition of other elements (i.e., ordinary brasses or special brasses), share with the bronzes the most important position among non-ferrous alloys. The influence of zinc upon the properties of copper is in the direction of increasing both strength and ductility, so long as certain limiting percentages are not exceeded, but these limiting percentages are much higher than in the case of tin, zinc being a less potent element than tin in similar amounts.

Fig. 318 presents a summary of the mechanical properties of the copper-zinc alloys. The curves are based upon the report of the Committee on Alloys of the United States Board to Test Iron, Steel, and Other Metals,* the fourth report of Professor W. C. Roberts-Austen to the Alloys Research Committee of the Institution of Mechanical Engineers,† and an independent study of the tensile strength of the copper-zinc alloys by Dr. J. M. Lohr.‡ The tests of the U. S. Test Board were made by Professor Robert H. Thurston, the specimens used being made from castings in the manner above described in connection with the tests of copper-zinc alloys quoted from the same source. The tests of the Alloys Research Committee were made upon specimens which had been mechanically worked, and those of Dr. Lohr were made upon cast specimens which were quenched in water immediately after solidification, in order to prevent the loss in strength incidental to the acquirement of a coarse crystalline structure during slow cooling.

The addition of zinc to copper gradually increases the strength in tension until about 30 or 35 per cent is present. Further additions rapidly increase the strength until a maximum beneficial effect is obtained with about 45 per cent of zinc. A rapid falling off in strength occurs with additions of zinc beyond 45 per cent, and the brasses containing more than about 50 per cent of zinc are brittle and worthless. (In the series of brasses tested by Thurston the gain in strength is fairly uniform with increase in zinc content up to a maximum at about 40 per cent of zinc, the strength thereafter falling off rapidly.)

The beneficial effect of preventing coarse crystallization by quenching the castings is shown by a comparison of the results of Lohr with those of Thurston, the strongest alloy of the former showing a tensile strength of about 72,000 pounds per square inch, with 45 per cent of zinc, as compared with one having a tensile strength of about 50,000 pounds per square inch with 40 per cent of zinc. The beneficial effect of mechanical working is also shown by a comparison of the curve representing the results of Roberts-Austen with that representing the results of Lohr.

The strongest cast brasses in compression appear to be those containing between 50 and 70 per cent of zinc; the maximum strength in

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* Report of U. S. Board to Test Iron, Steel, and Other Metals, 1881.

† Proceedings of the Institution of Mechanical Engineers, 1897.

‡ Journal of Physical Chemistry, Vol. 17, No. 1, Jan., 1913.

flexure corresponds to the maximum tensile strength; and the maximum ductility is shown by alloys containing from about 25 to about 35 per cent of zinc. The strongest brasses show very low ductility.

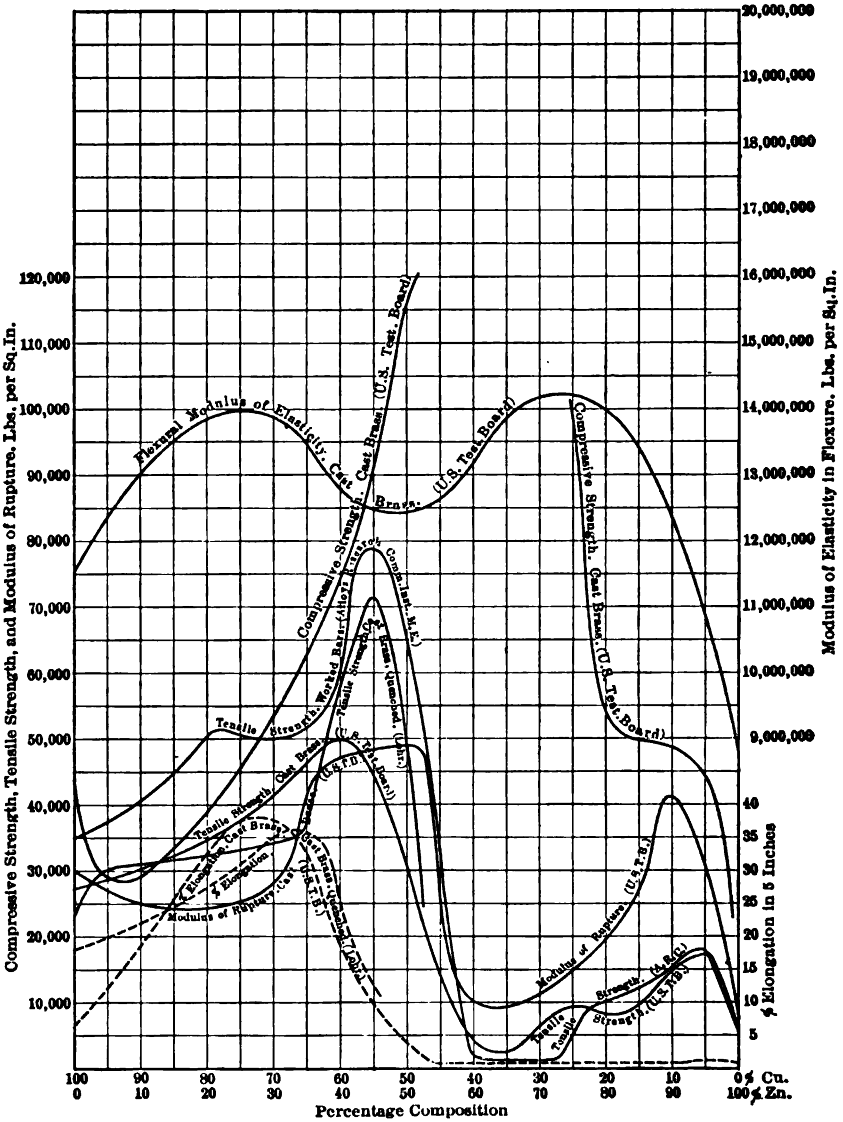

FIG. 318.—Properties of the Copper-Zinc Alloys.

A comparison of the curves of Fig. 318 with those of Fig. 316 shows that the best of the brasses excel the best of the bronzes in tensile strength and ductility, but the latter seem to excel in compressive strength.

The various common commercial forms of brasses may be classified, as follows according to composition and uses:

Tombac and *pinchbeck* contain 85 to 90 per cent of copper and 15 to 10 per cent of zinc. They take a good polish and are principally used for ornaments, imitation of gold, etc.

Hard brazing metal contains 80 to 90 per cent of copper and 20 to 10 per cent of zinc. That containing 20 per cent of zinc is known as " quarter metal " and is considerably used for the purpose indicated by the name.

Red brass usually contains about 80 per cent of copper and 20 per cent of zinc. The name is used loosely, however, to cover any of the high-copper brasses which possess a reddish color, especially after pickling in acid. This class of brass is much used for ornamental work and soft castings.

Standard brass contains about 66 to 70 per cent of copper and 34 to 30 per cent of zinc. It is the most generally useful and most commonly used of all brasses. It is very ductile, works well hot or cold, and can readily be rolled into sheets and drawn into tubes or wire. It is less corrosive than any of the brasses of lower copper content, and is especially adapted for use in locomotive and steamship boiler and condenser tubes. Practically all ordinary sheet brass and drawn brass is of this composition, and the best of the brass castings contain about 66 or 67 per cent of copper.

Muntz metal is a brass containing 60 per cent of copper and 40 per cent of zinc. It can only be rolled hot, but was formerly much used as a sheathing for wooden vessels. Sea water attacks it and forms zinc salts, which prevent the fouling of the bottoms of ships by living organisms such as barnacles, etc.

Yellow brass contains from 48 to 56 per cent of copper and 52 to 44 per cent of zinc. A mixture of approximately equal proportions of the two constituents is commonly used in making brass castings which do not require great strength or toughness. At a red heat yellow brass becomes so brittle that it may be easily pulverized, and in this form is much used for yellow solder for brazing purposes.

White brass solder contains 34 to 44 per cent of copper and 66 to 56 per cent of zinc. It is extremely weak and brittle and is used only in a powdered condition for brazing purposes.

White brass contains less than 10 per cent of copper and more than 90 per cent of zinc. The metal possesses most of the characteristics of zinc, but is somewhat hardened and strengthened by the small amount of copper used, the coarse crystalline structure of cast zinc being largely destroyed. The material is principally used in making ornaments which are plated with bronze and sold under the name " French bronze."

545. Special Brasses. *Copper-zinc-lead brasses.* The addition of small percentages of lead softens brass and renders it more easily cut by machine tools. The presence of the lead lowers the strength and decreases the ductility considerably. More than 5 per cent of lead cannot be profitably used because of the danger of segregation, and the usual addition is not in excess of 3 per cent.

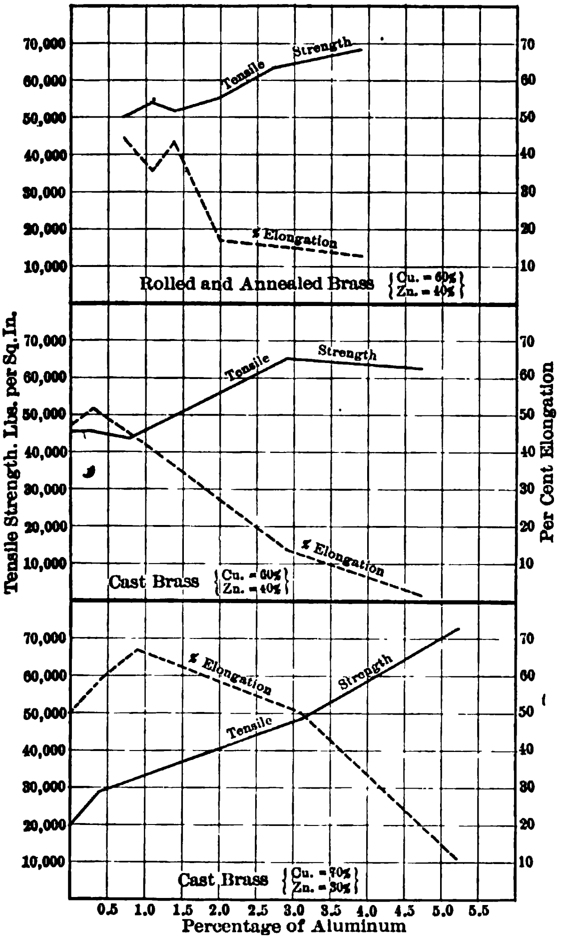

FIG. 319.—Effect of Aluminum on Tensile Properties of Brass. (Guillet.)

Copper-zinc-aluminum brasses. Aluminum is added to brass in amounts up to about 5 per cent with beneficial effects upon the tensile properties. The tensile strength and elastic limit are considerably raised, and the hardness increased and ductility decreased. The effect of aluminum upon the tensile strength and ductility of rolled and cast brass is exhibited by Fig. 319 which is based upon tests reported by M. Guillet.* The addition of aluminum is also beneficial in that it facilitates the making of good brass castings. Aluminum brass is principally used in making castings for machinery, marine work, etc., for forgings, and for rolled

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* " Étude Industrielle des Alliages Metalliques," 1906.

bars, plates and shapes designed for any purpose requiring a strong brass, or a strong and non-corrosive metal.

Copper-zinc-manganese alloys. Manganese bronze. The most valuable copper-zinc alloy in use at the present time is the so-called "Manganese Bronze." The presence of small amounts of manganese in the finished alloy is beneficial to strength in a measure, but the commercial alloy known by this name is simply a brass with which a small amount of manganese, in the form of ferro-manganese, or manganese-copper produced in the electric furnace, has been incorporated while molten for the sake of the important deoxidizing effect which the manganese exerts. The resultant alloy usually contains no manganese, or only a trace, because it has been oxidized out and fluxed off.

The specifications of the American Society for Testing Materials * for manganese bronze ingot metal for sand castings call for an alloy having the following composition and tensile properties:

Chemical Composition. Per cent.	Minimum Tensile Strength. Lbs. per Sq.in.	Minimum Elongation in 2 Inches. Per cent.
Copper, 53–62 Zinc, 36–45 Aluminum, 0.05–0.5 Lead, not over 0.15	70,000	20

The average composition of the commercial alloy, according to Mr. C. R. Spare,† is about 56 to 57 per cent of copper, 38 to 40 per cent of zinc, about 1 per cent of tin and 1½ per cent of iron. The iron is present inadvertently, owing to the use of ferro-manganese as the deoxidizer, and a little aluminum is introduced to facilitate the making of cast manganese bronze, but is considered undesirable in bronze intended for forging or rolling.

The range of composition of various brands of manganese bronze is quite wide and the properties of the metal vary accordingly. A soft grade is made especially for use in situations where it must withstand shock and vibration, as in naval ordnance construction. This metal has a tensile strength of about 60,000 pounds per square inch with an elongation of 40 to 50 per cent in 2 inches. A very hard grade is made which has a tensile strength of 90,000 to 100,000 pounds per square inch with elongation of 15 to 25 per cent.

The average grade of manganese bronze shows about the following properties:

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* Yearbook, 1914.

† Proc. Am. Soc. Test. Matrls., Vol. 8, p. 395.

	Tension.			Compression.	
	Elastic Limit. Lbs. per Sq.in.	Tensile Strength. Lbs. per Sq.in.	Elongation, 2 Ins. Per cent.	Elastic Limit. Lbs. per Sq.in.	Compressive Strength. Lbs. per Sq.in.
Cast manganese Bronze	30,000 to 40,000	70,000 to 80,000	20 to 35	35,000 to 40,000	90,000 to 100,000
Rolled or forged manganese bronze	40,000 to 50,000	80,000 to 110,000	15 to 30	50,000 to 60,000	130,000 to 150,000

Probably no other metal or alloy possessing equal strength and toughness can be cast in intricate forms so successfully as can manganese bronze. In addition, it is particularly resistant to corrosion by sea water and alkali waters, and is proof against attack by dilute acids. Manganese bronze is very commonly used for steamship propellers, and is much used for other ship fittings, for piston rods, shafts and axles, and for all manner of castings, forgings, etc., used in general machine construction, and in locomotive and automobile construction. It has many applications in subaqueous work of various types, and has also been found to be one of the best materials obtainable for the blades of high-speed steam turbines. For the latter application it not only possesses the high strength required, but also resists the corrosive action of high pressure steam very well.

Copper-zinc-iron alloys. Two brass alloys containing iron have been commonly used: *Sterro metal* contains about 60 per cent of copper, 38 to 38.5 per cent of zinc, and 1.5 to 2 per cent of iron. *Delta metal* varies in composition, but usually contains about 55 per cent of copper, 41 per cent of zinc, 3 per cent of iron, and 1 per cent of manganese, phosphorus, and other elements. These metals, particularly the delta metal, possess a considerably higher strength and better working qualities than the brass would possess without the iron addition. They are also more resistant to corrosion. They possess, to a lesser extent, the characteristic properties of manganese bronze and aluminum brass, and have been adopted for the same class of uses, principally on marine construction.

Other special brasses. Vanadium is a metal which is only very rarely used in brasses. *Phosphorus* is also occasionally used in small amounts for the purpose of deoxidizing the copper, but neither vanadium brass nor phosphorus brass are alloys possessing any commercial importance. A number of quite important alloys of copper, zinc, and nickel are made and sold—usually under the name of "German silver." These latter alloys will be considered under the head of *Nickel Alloys.*

BINARY ALLOYS OF COPPER OTHER THAN BRONZES AND BRASSES

546. Copper-Aluminum Alloys. The alloys of copper and aluminum are the most valuable of the copper alloys other than the bronzes and brasses. The principal commercial alloy of copper and aluminum is the so-called *aluminum bronze,* which usually contains from 90 to 95 per cent of copper and 5 to 10 per cent of aluminum. Since no tin is present, the alloy is not really a bronze, but it is, nevertheless, commonly called "aluminum bronze," perhaps on account of its resemblance to some of the bronzes in its properties.

The characteristics of the copper-aluminum alloys have been made the subject of an extremely painstaking investigation by the Alloys Research Committee of the Institution of Mechanical Engineers. The results of this investigation constitute the Eighth Report of this Committee.* Fig. 320 constitutes a summary of the results obtained in a portion of the investigation of tensile properties of a series of copper-aluminum alloys containing up to 13 per cent of aluminum.

The addition of aluminum to copper is shown to be responsible for a gradual raising of the tensile strength and yield-point, and a rapid increase in ductility, until about 7.35 per cent of aluminum is present. Further additions cause a more rapid raising of the strength and yield-point, accompanied by a very rapid decrease in ductility, until an alloy of maximum strength (60,000 to 74,000 pounds per square inch for castings) is reached with about 10 per cent of aluminum present. With additions of aluminum beyond 10 per cent, the strength rapidly falls off and the ductility becomes practically *nil,* the yield-point coinciding with the ultimate strength with about 13 per cent of aluminum present.

Comparing the properties of the castings made in sand with those cast in chills, it appears that chilling scarcely affects the properties of alloys containing less than 6 per cent of aluminum, but raises the strength and yield-point of the higher-aluminum alloys in proportion to the aluminum content. The strength of the chilled 10 per cent aluminum alloy is about 20 per cent higher than that of the corresponding sand-cast alloy.

The $1\frac{1}{4}$-inch rolled bars were produced by hot rolling of an ingot cast 3 inches in diameter, but turned down to about $2\frac{13}{16}$ inches, so that the reduction in rolling was from this diameter down to $1\frac{1}{4}$ inches. The rolled bars show practically the same ductility as the cast bars, but excel the latter slightly in tensile strength and yield-point. The beneficial

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* Proceedings Institution of Mechanical Engineers, 1907, p. 57.

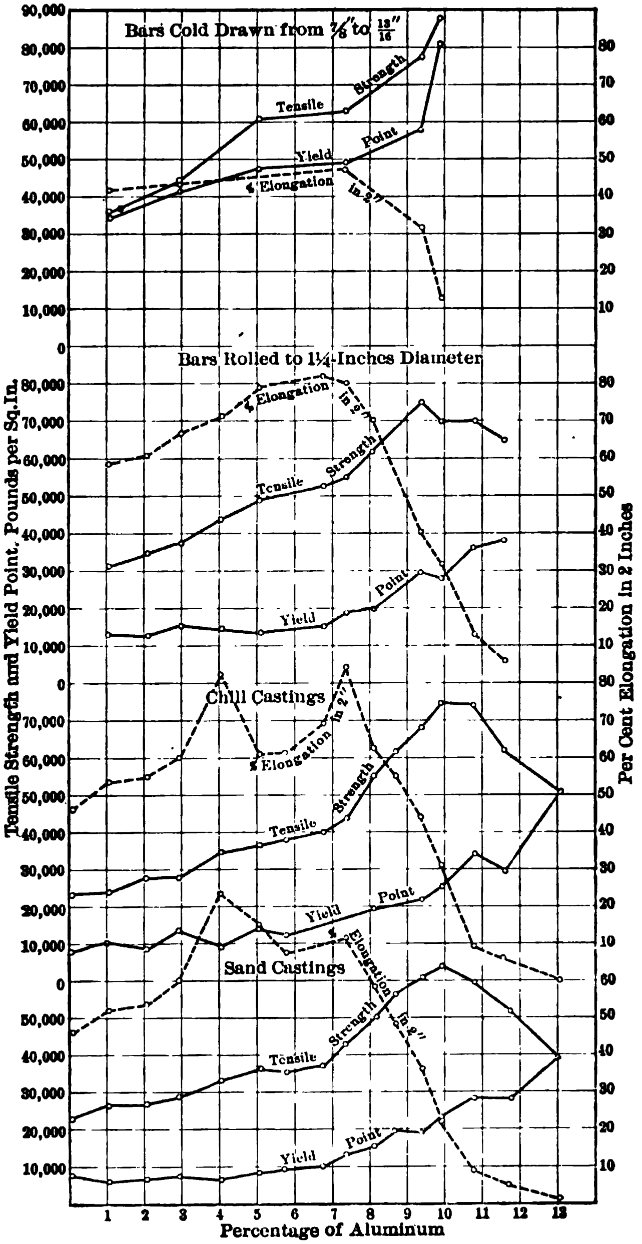

Fig. 320.—Tensile Properties of Aluminum Bronzes. (Alloys Research Committee.)

effect of rolling was found to be only slightly increased when the reduction in rolling was continued down to $\frac{13}{16}$ inch diameter.

The cold-drawn bars were produced by rolling hot from $1\frac{1}{4}$ inches down to $\frac{15}{16}$ inch, cold drawing to $\frac{7}{8}$ inch, annealing, and then cold-drawing down to $\frac{13}{16}$ inch. The effect of cold-drawing to this moderate extent appears to be a moderate increase in tensile strength, a great raising of the yield-point, and a great loss of ductility.

The effect of slow cooling from 800° C., and the effect of quenching from the same temperature were also investigated and led to the conclusion that slow cooling from this temperature has no effect upon alloys containing less than 7.35 per cent of aluminum, and injured the higher-aluminum alloys, owing to coarse crystallization and consequent brittleness. Quenching was found to have no effect upon the alloys below 7.35 per cent aluminum, but greatly raised the tensile strength and yield-point, and lowered the ductility of the higher-aluminum alloys.

By way of summing up the discussion it may be stated that the aluminum bronzes containing less than 7.35 per cent of aluminum show moderate strength, a yield-point that is relatively low, and a ductility that is remarkably high. The high-aluminum alloys (8 to 11 per cent aluminum), show a remarkably high strength, a relatively low yield-point, and low ductility.

Most of the aluminum bronzes work well in the foundry, and may easily be rolled below a bright red heat, forged at a low red heat, or drawn into bars, shapes, sheets, tubes, wires, etc. The metal is highly resistant to corrosion and has therefore been used on marine works and as ship's fittings, including propeller blades. In ordinary machine construction and in automobile construction it has found many special uses, and, because of the peculiar smooth unctuous surface which it acquires, it has been found to be an excellent anti-friction metal. The high-copper aluminum bronze is much used as imitation gold.

547. Binary Alloys of Copper with Manganese, Phosphorus, Silicon, etc. Alloys of copper are occasionally made with manganese, phosphorus, silicon, vanadium, chromium, tungsten, antimony, bismuth, lead, arsenic, etc. None of these possess special properties which render them particularly useful commercially, and no space therefore will be herein devoted to a consideration of their characteristics.

ALLOYS OF ZINC, LEAD, TIN, ALLUMINUM, AND NICKEL

548. Binary Alloys of Zinc. (Non-cuprous.) Zinc forms no binary alloys of commercial importance with the exception of the brasses. The character of the various other binary zinc alloys may be briefly indicated as follows:

Lead cannot readily be alloyed with zinc in a binary alloy. *Tin* may be alloyed with zinc with care, forming white metals of almost any composition. These alloys have little practical importance, however, and are rarely made on account of the high cost of tin. Alloys of *antimony* and zinc are difficult to make, and have little value because of their brittleness and the readiness with which they are oxidized. *Bismuth* forms alloys with zinc which are extremely brittle and worthless.

549. Binary Alloys of Lead. (Non-Cuprous.) *Lead-tin alloys.* Lead and tin alloy in all proportions, the most important series of alloys being those used as *plumber's solder*, and which contain from 33 to 50 per cent of tin. The best solder for wiping joints in lead pipe is one containing about 2 parts of tin to 1 part of lead, but, owing to the expensiveness of tin, the content of this constituent is often reduced. The especial value of the lead-tin solders lies in the fact that the metal passes through a pasty stage in solidifying, the lead solidifying gradually before the entire mass freezes. Another alloy of lead and tin formerly much used for making various domestic utensils, slush castings, etc., is that which is called *pewter*. As tin is added to lead the latter is hardened and strengthened gradually until an alloy of maximum strength is reached with about 70 to 75 per cent of tin present. Ordinary pewter contains from 50 to 80 per cent of tin, the quality being best when the tin content exceeds 70 per cent. A little antimony or copper may be used to harden pewter.

Lead-antimony alloys. Antimony is often present in lead accidentally, as has been above noted, the resultant impure lead being known as " antimonial lead " or " hard lead " which may be used as type metal with or without the addition of tin, bismuth or copper. Antimony hardens lead very rapidly and in large amounts makes it very brittle, but at the same time forms an alloy which casts well and takes a very sharp impression of the mold. The average type metal contains about 17 per cent of antimony and may also contain from 10 to 20 per cent of tin or small amounts of bismuth, copper, etc. Lead-antimony alloys used for shot, bullets, etc., contain about 12 to 16 per cent of antimony.

Lead-bismuth alloys. Lead-bismuth alloys are easily made, so long as the proportion of bismuth is less than that of lead. The resultant alloys exceed pure lead in ductility and malleability, but have no important commercial applications.

Lead-cadmium alloys are seldom produced, except accidentally, and possess no commercial importance.

Lead-arsenic alloys are made intentionally for only one purpose—the making of shot. The addition of from 0.5 to 1 per cent of arsenic renders the lead more fusible, lengthens the time of solidification, thus facilitating the assumption of a spherical form by the lead in its drop in the shot tower, and makes the metal, when solidified, somewhat harder than pure lead.

550. Binary Alloys of Tin. (Non-cuprous.) The principal classes of binary tin alloys have been considered above. *Cadmium* forms alloys of little practical value, and *antimony* forms alloys which are similarly without commercial importance with the exception of one alloy, known as *Brittannia metal,* which is used to a slight extent for ornamental castings and stamped or wrought forms which are usually polished or plated. The usual composition of this alloy is 80 to 90 per cent of tin and 5 to 15 per cent of antimony, the balance of the composition being made up of small amounts of copper, zinc, etc., added for the sake of their hardening effect. The binary alloys of tin with *bismuth, nickel,* etc., possess no great industrial importance. In general, none of the alloys of tin, excepting the brasses and the tin-lead alloys, possess valuable properties, and their high cost therefore bars their use where cheaper alloys will serve as well.

551. Aluminum Alloys. A great number of metals, and some non-metallic elements, are added to aluminum for the purpose of strengthening or hardening it, without materially increasing its weight. These alloys are generally classed as *light aluminum alloys.*

Aluminum-zinc alloys are the most valuable and also the cheapest of the light alloys. Proportions up to about 33 per cent of zinc are used, the most ductile and malleable alloys containing less than 15 per cent of zinc, while those containing higher zinc contents are still useful in castings which permit of a certain degree of brittleness. These alloys are readily made, are harder and more fusible than aluminum, and are still very light.

The properties of the aluminum-zinc alloys have been exhaustively studied by the Alloys Research Committee * and a summary of a portion of their report is presented by Fig. 321. It is shown by the diagram that all of the alloys containing more than about 15 per cent of zinc are very non-ductile and brittle, and that even when ductility is unimportant no gain in strength, or at least in yield-point, is obtained by increasing the zinc content beyond about 30 per cent. The beneficial effect of hot and cold working of these alloys is shown by the diagram of Fig. 322.

Aluminum-copper alloys. Copper is one of the most commonly used hardening agents in aluminum alloys, the amount used in binary alloys rarely exceeding about 6 or possibly 8 per cent. The copper raises the strength and the yield-point considerably, but causes a rapid loss of ductility.

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* Tenth Report, Proc. Inst. Mech. Engrs., 1912, p. 319.

The properties of this series of alloys have also been studied by the Alloys Research Committee, and a portion of their report is summarized

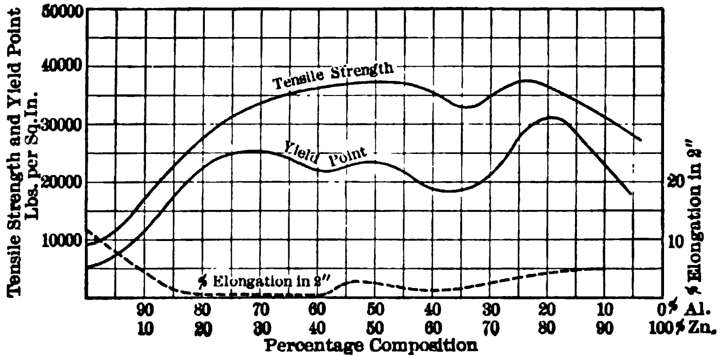

FIG. 321.—Tensile Properties of Aluminum-Zinc Sand Castings. (Alloys Research Committee.)

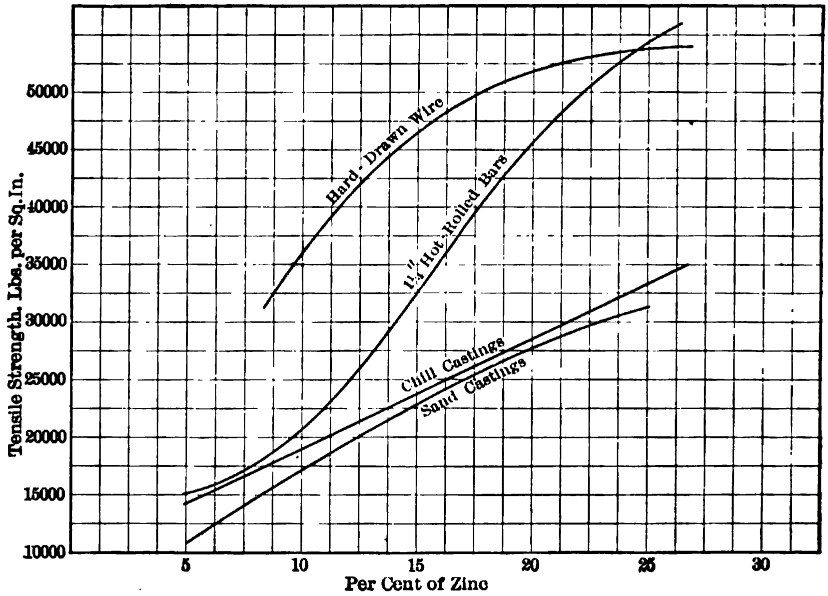

FIG. 322.—Effect of Mechanical Working on Strength of Aluminum-Zinc Alloys. (Alloys Research Committee.)

by the diagrams of Fig. 323. A comparison of this diagram with the diagrams of Figs. 321 and 322 shows that the aluminum-copper alloys are considerably inferior to the aluminum-zinc alloys in strength, but greatly excel them in ductility. The yield-point also is not relatively nor actually as high in the copper alloys as in the zinc alloys.

Aluminum-magnesium alloys. The alloy of aluminum and magnesium possessing the most valuable properties is one containing less than 2 per cent (usually about 1.6 per cent) of magnesium. This alloy is

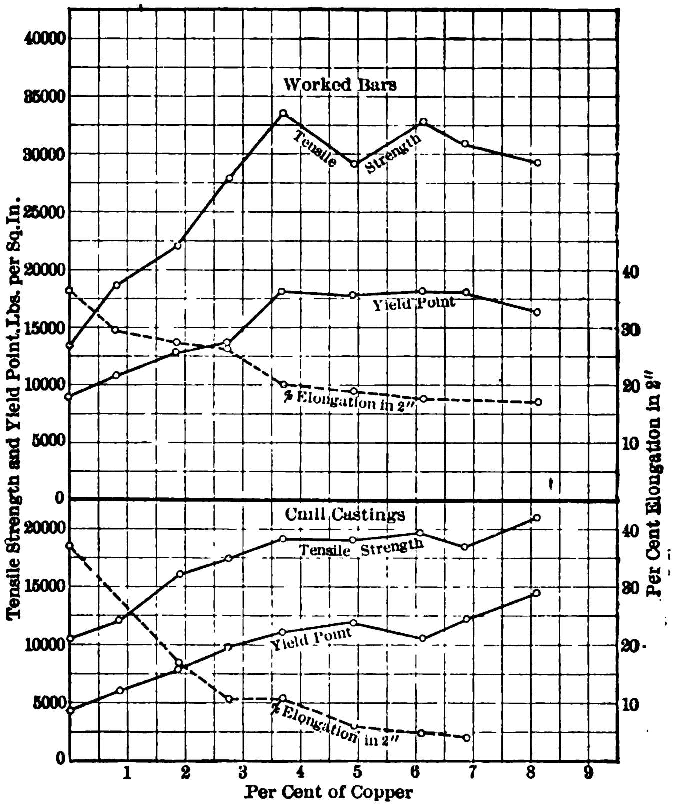

FIG. 323.—Tensile Properties of Aluminum-Copper Alloys. (Alloys Research Committee.)

slightly lighter than pure aluminum, but shows a tensile strength of 25,000 to 40,000 pounds per square inch when cast and rapidly cooled or when rolled without annealing. The commercial alloy of aluminum and magnesium usually contains small percentages of copper, nickel, tin or lead. Mr. J. W. Richards * quotes tests of aluminum-magnesium alloys showing the following properties:

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* Proc. Am. Soc. Test Matrls., Vol. 3, p. 245.

	2 Per cent Mg.		4 Per cent Mg.		6 Per cent Mg.	
	Tens. Str. Lbs. per Sq.in.	Per cent Elong.	Tens. Str. Lbs. per Sq.in.	Per cent Elong.	Tens. Str. Lbs. per Sq.in.	Per cent Elong.
Cast in sand	17,900	3.0				
Cast in chills	28,600	2.0	28,600	2.6		
Castings water chilled	40,000	1.0	......	....	57,600	1.0
Annealed sheet	25,600	18.0	28,200	8.0	28,100	17.0
Hard sheet	41,300	2.7	44,900	2.1	44,100	1.0

	8 Per cent Mg.		10 Per cent Mg.	
	Tens. Str. Lbs. per Sq.in.	Per cent. Elong.	Tens. Str. Lbs. per Sq.in.	Per cent Elong.
Cast in sand	....	....	21,400	2.4
Cast in chills	....	....	33,600	3.4
Castings water chilled	54,900	1.6	61,100	4.2
Annealed sheet				
Hard sheet				

Aluminum-copper-zinc alloys have been produced commercially to a slight extent as light casting alloys. Various alloys of this type contain from 9 to 27 per cent of zinc and 3 to 5 per cent of copper. The Alloys Research Committee * found the alloy containing about 25 per cent of zinc and 3 per cent of copper to possess quite valuable properties. When cast in sand or in chills it showed a tensile strength of 36,500 and 40,440 pounds per square inch, respectively, but was almost absolutely non-ductile. When hot rolled, however, it developed a tensile strength of over 60,000 pounds per square inch with a yield point of about 44,000 pounds per square inch, and an elongation of about 16.5 per cent.

Aluminum-copper-manganese alloys have not attained any considerable importance as commercial alloys, but have been made the subject of special study by the Alloys Research Committee † principally because, from the analogy of aluminum bronzes to ordinary copper-tin bronzes, it was anticipated that the addition of the strongly reducing manganese might benefit the former, as it is known to benefit the latter. The results of the investigation show that manganese does have the effect anticipated in a measure, but does not alter the properties of aluminum bronze to nearly the same extent that it does ordinary bronze.

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* Appendix to Tenth Report.

† Ninth Report, Proc. Inst. Mech. Engrs., 1910, p. 119.

The strength of the corresponding copper-aluminum alloy is only slightly raised by the addition of manganese below 4 per cent, but the ductility is considerably decreased.

(The composition of the ternary alloys above discussed is about 9 per cent of aluminum, less than 4 per cent of manganese, and the balance copper. It might therefore be more properly called a copper alloy than an aluminum alloy, and cannot be classed among the light alloys.)

Minor alloys of aluminum. Alloys of aluminum with nickel, tin, manganese, tungsten, chromium, titanium, silver and antimony have been made commercially, but none possess such valuable distinctive properties as to have won for them an important place among the light alloys. The commercial alloy known as "nickel aluminum alloy" usually contains only a trace of nickel, and is for the rest an alloy of 2 to 7 or 8 per cent of copper in aluminum.

552. Alloys of Nickel. German Silver. The principal nickel alloys not considered above are a large number of alloys of copper, nickel, and zinc, to which other metals are sometimes added in small amounts, and which are known collectively as *German silver.* This alloy is chiefly valuable because of its silvery white color and its non-corrodibility.

A typical composition of German silver is nickel 18 to 20 per cent, zinc 28 to 32 per cent, and copper 50 to 56 per cent. The whitest metal is obtained with about 25 to 30 per cent of nickel and 20 to 25 per cent of zinc, but, since the nickel is the most expensive constituent, its proportion is often cut down. The alloy containing 30 per cent of zinc and about 18 per cent of nickel is quite white, makes smooth sound castings, and is best from the standpoint of malleability and toughness. Aluminum in amounts up to about 25 per cent makes the metal more fluid while molten and is therefore desirable in castings. It also toughens the cooled casting. Iron hardens the metal, and makes it whiter when present in amounts not exceeding 1 to 2 per cent. Tungsten up to 1 or 2 per cent is also occasionally used to form an alloy called "platinoid" which has very high electrical resistance, and is used for electrical purposes.

German silver is principally used in the making of domestic utensils, table ware, decorative objects, physical and scientific instruments, coinage, etc.

553. Special Bearing or Anti-friction Metals. The bearing bronzes and the lead-antimony bearing metals have been considered above. Aside from the bearing bronzes, the best-known bearing metals are those composed of tin, copper, and antimony which are known as *Babbitt metal.* The composition of this alloy is extremely variable, but the usual limits are tin 80 to 90 per cent, copper 3 to 10 per cent, and antimony 8 to 12 per cent. The quantity of antimony should always exceed the amount of copper in order to prevent brittleness. The ultimate constitution of Babbitt metals appears to be that of a ground mass of soft tin with hard crystals of a copper-antimony compound and a tin-antimony compound scattered through it. The hard particles carry the load and resist wear, while the soft ground mass allows the metal to adjust itself to the surface of the shaft and equalize the bearing pressure

Alloys of lead, tin, and antimony have been considerably used as bearing metals, the best compositions being those containing 10 to 15 per cent of antimony, 10 to 20 per cent of tin, and the balance lead.

Alloys of lead, copper, and antimony have occasionally been used as bearing metals where heavy loads are encountered. A typical composition is 65 per cent of lead, 10 per cent of copper, and 25 per cent of antimony.

Alloys of zinc, tin, and antimony, and *alloys of lead, tin, and bismuth*, have been used as bearing metals, but their general application has been very limited on account of a tendency toward fragility on the part of the former, and the high cost of bismuth in the case of the latter..

CHAPTER XVIII

TIMBER *

GENERAL

554. Timber as a Material of Engineering Construction. Timber has been one of the primary materials of engineering construction since the earliest times, and, despite the fact that it has been largely superseded by concrete and steel in the construction of certain classes of structures, still the total consumption of timber for structural and other commercial purposes is steadily increasing year by year.

In spite of the great number of species of trees (something like 500 grow in the United States alone), only a very limited number of kinds of timber are of great commercial importance, the larger part of all timber used structurally being derived from only twelve distinct species of trees—those commonly known as *pine*, *fir*, *oak*, *hickory*, *hemlock*, *ash*, *poplar*, *maple*, *cypress*, *spruce*, *cedar*, and *walnut*. These common names of species usually include several varieties, which may show quite diverse characteristics and possess, therefore, very different values as timbers of construction.

Much confusion exists as to the common nomenclature of woods, the same species or variety being known by many different local names, and different species are sometimes known in different localities by the same name. The recognized botanical Latin nomenclature affords a dependable guide to species, but is too cumbersome for general use. In consequence, various national societies like the American Society for Testing Materials and the American Railway Engineering and Maintenance of Way Association have adopted standard classifications of those particular structural timbers most used commercially, listing the various common names of a given species under a single name whose meaning is thus defined.

Any study of the characteristics and properties of woods must include

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* The writer is indebted to the publications of the U. S. Forest Service for most of the data upon which this chapter is based. The admirable text-books of Mr. Samuel J. Record, " Economic Woods of the United States," 1912, and " The Mechanical Properties of Wood," 1914, have been frequently consulted, however.

some information concerning trees. The point of view of the engineer need not be that of the botanist, and his study may be confined to the general features, conditions and manner of growth of a limited number of species of trees, but physical and mechanical properties of timbers are closely dependent upon structure, and structure is not only dependent upon variety, species, and genus, but within a given variety, upon conditions of growth—climatic and soil conditions. No detailed botanical consideration of trees will be included herein, but a general classification of trees will be made, together with some study of growth and structure.

TIMBER WOODS. GROWTH AND STRUCTURAL CHARACTERISTICS

555. Classes of Trees. All trees are primarily divided into two botanical groups according to their manner of growth:

Exogenous trees, or *exogens*, increase in diameter by the formation between the old wood and the bark of consecutive rings or layers of new wood which envelops the entire living portion of the tree. They lengthen by a sort of telescopic extension at the tips, each consecutive layer increasing the length because of its conical form. Practically all classes of commercially important timbers are derived from trees of this group.

Endogenous trees, or *endogens*, grow both diametrically and longitudinally, principally the latter, by the addition of new wood fiber intermingling with the old. Most endogens are small plants like corn, sugar-cane, wheat, rye, etc., but others like the palm, the yuccas and the bamboo have some value as a source of structural material.

Exogenous Trees

556. Conifers. *Conifers* or *gymnosperms*, the needle-leaved, naked-seeded trees, form an important portion of our timber trees, comprising principally the pines, the spruces, fir, hemlock, larch, tamarack, cedar, cypress, and redwood. The conifers are widespread throughout the northern hemisphere. They are usually light and soft, hence often called " soft woods." The trees may invariably be recognized by their needle leaves, their resinous bark and the cones which they bear. They are for the most part " evergreens." (The larch and the bald cypress are not evergreens, as they shed their needles annually, and some of the pines, some spruces, and tamarack are not soft woods but are quite hard.)

557. Broadleaf Trees. *Broadleaved* trees or *dicotyledons* (two seed-leaves) provide a source of timber second in importance only to the conifers. They comprise many varieties of oak, ash, hickory, poplar (cottonwood), maple, walnut, elm, chestnut, birch, beech, cherry, locust, basswood (linden), whitewood (tulip), sycamore, catalpa, butternut, buckeye, alder, willow, eucalyptus, gum, horse-chestnut, holly, boxwood, laurel, lignum-vitæ, mahogany, satinwood, and many other species of lesser commercial importance. The broadleaf trees are found in widespread areas scattered over most of the globe. They are usually heavy and hard, hence often called "hard woods," and, as a rule, they are deciduous, although many broadleaf trees are evergreen in certain climates. The broadleaf woods are not used for structural purposes to anywhere near the same extent as the conifers, but are specially adapted to use for interior finishing, cabinet work, furniture, etc. (Many broad-leaved woods are neither heavy nor hard, as for instance poplar, chestnut, basswood, whitewood, willow, etc.)

ENDOGENOUS TREES

558. Endogenous Trees. Monocotyledons. *Monocotyledonous trees* or *monocotyledons* (one-seed-leaf) are largely confined to tropical or semi-tropical regions. The palms, because of their long straight stems and comparative immunity from the destructive action of the teredo (a form of marine wood-borer which is very active in some waters), are sometimes locally used as piles, but have practically no other commercial uses. Only a few varieties are native to the United States. The yuccas find little application to commercial uses except as paper-pulp and as a veneer adapted to certain special uses where its lightness and flexibility are advantageous. The bamboo is not native to the United States and, where found, has been transplanted from Asia. The bamboo grows with extreme rapidity, but requires years to harden after its growth is attained. Bamboo has many commercial uses in Asia, particularly in Japan and in China, where it is even used structurally to a considerable extent. Its use in the United States is largely confined to small household articles, furniture, etc.

EXOGENOUS GROWTH OF WOOD *

559. Pith, Wood, and Bark. The section of any exogenous tree exhibits first a central portion composed of loosely aggregated thin-walled cells called the pith. It is circular, star-shaped, ovoid, or tri-

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* For a much more detailed treatment of the growth and structural elements of wood see Record's " Economic Woods of the United States." The present discussion is largely based on this work.

angular in shape; black, red brown, or gray in color; usually of small diameter, and does not increase in size after the first year. It probably assists the life processes of the tree at first by alternately storing and giving up plant food like starch and tannin, but it becomes inactive after a very few years and sometimes the pith cells disappear, leaving a pith cavity. Often the pith becomes compressed and is sometimes scarcely evident in sections of mature trees.

Outside the pith the wood appears in concentric zones or rings of annual growth, the demarkation between which is evident because of the different structure of the wood slowly formed toward the end of one season and that rapidly formed in the succeeding spring. The various elements entering into the wood structure will hereinafter be considered in some detail.

The outermost portion or periphery of the section is formed by material of variable and very complex structure called the bark. The origin, growth, and structure of the bark will be briefly considered in the discussion which follows. The bark of many trees possesses a distinct commercial value. Many trees furnish bark for medicinal purposes, others, like the hemlocks and the oaks, supply a great part of the tannin used in the leather industries, several serve as a source of coloring matter, others furnish fiber for cloth and cordage, and one particular species provides the cork of commerce.

560. Primary Wood, Cambium, and Secondary Wood. The tissue which forms the apex of a growing shoot is composed of simple thin-walled similar cells called the *primordial meristem.* This tissue soon becomes differentiated into three portions known as the *protoderm* (outermost), the *procambium strands,* and the *ground meristem* (innermost), respectively. The protoderm soon changes into *epidermis,* the outermost portion of newly formed bark; the ground meristem forms the *pith,* the *primary rays,* that portion of the bark called the *pericycle,* and between epidermis and pericycle, the *primary cortex.* The procambium strands become *vascular bundles,* which occupy the zone between pith and pericycle and are separated from each other only by the primary rays. The vascular bundles comprise three classes of tissue, the *phloem,* which constitutes the innermost portion of the bark; the *cambium,* that layer of generative cells between bark and wood; and the *xylem* or wood fiber, which constitutes all the woody portion between pith and bark. These tissues, being formed prior to the development of the cambium, make up the *primary wood,* so called in contradistinction to the *secondary wood,* which is generated by the cambium.

The epidermis is destroyed at an early period and replaced by *cork,* formed by a *cork cambium* originating in the epidermis or in the cells just beneath. The development of cork cuts off successive portions of the cortex which dry up and ultimately scale off as outer bark. The pericycle is to a large extent made up of fibrous tissue which imparts toughness to the bark and protects the delicate tissues beneath. The phloem is made up of several elements which resemble corresponding elements in wood. It contains tubes similar to the *vessels* in wood, which assist the life processes of the tree, particularly by allowing a downward circulation of food materials.

The portion of the original vascular bundles called the cambium, which is capable of generation and growth, is originally isolated in the several bundles, but ultimately becomes united in a continuous sheath separating the entire woody cylinder from the bark. The cambium is made up of thin-walled cells which are particularly delicate when saturated with sap during the period of most vigorous growth. The cambial cells, by division and development, generate new wood or xylem on the one side, and bark or phloem on the other.

All wood formed from the cambium is called *secondary wood,* and this constitutes all but a negligibly small part of the wood of a tree. The secondary wood provides mechanical support for the tree, affords a medium for the ascent of sap from the roots, and alternately stores and gives up the starchy foods necessary to the life processes of the tree.

The structure of secondary wood is quite complex, and is subject to wide variation, but is invariably made up of some or all of the following four distinct elements, viz., (1) *vessels,* (2) *tracheids,* (3) *wood fibers,* and (4) *parenchyma.*

561. Structural Elements of Wood. *Vessels* are tubular elements formed by the union of original cambial cells, the end walls of which have become wholly or partly absorbed, thus giving rise to a continuous tube of indeterminate length. The point of union of the segments is always marked by a constriction in the walls, and its plane may be either square or oblique. In the latter case the perforation between the segments is often *sclariform,* that is, the opening is partially closed by a series of parallel cross-bars. In most cases the walls of the vessels are provided with many small gaps called *pits.* A pit is simply a small portion of the wall where the original cellulose membrane of the primary cambial cell has not become thickened by the addition of lignin. A canal is thus formed, closed only by the thin membrane of the primary cell wall. This canal often widens toward the primary cell wall, and, if the widening occurs suddenly, the pit is called a *bordered pit,* otherwise, it is a *simple pit.* The function of the pits is to facilitate the passage of water and food between adjacent cells. (Water only in the case of pits in the walls of vessels.)

The vessels are always continuous for great lengths, often the entire length of the tree. In diameter they are sometimes very small (less than 0.005 inch) as in the poplar, in others, like the chestnut they are large (0.01 to 0.03 inch) and visible to the naked eye as pores in the cross-section.

The function of the vessels is to provide unobstructed passages through which water may ascend from the roots to the branches. They contain no protoplasmic matter after becoming fully developed, but those in the older part of the wood may become filled with gums, resin, lime-carbonate, etc.

Tracheids are elongated single cells of tubular form, closed at their ends and characterized by the presence of bordered pits in their side walls. They are polygonal in cross-section, arranged in radial rows, and become flattened and thicker-walled toward the end of each season's growth, the *lumen* or interior opening being therefore smaller toward the periphery of each growth ring.

The tracheids form the bulk of the wood of conifers, wherein they attain a length of from 0.1 to 0.2 inch. Their diameter seldom exceeds 0.002 inch. In broad-leaved woods the tracheids are much less important elements than in the conifers, and may even be entirely lacking. If present, they are much smaller and less uniform in size, shape, and arrangement.

The function of the tracheids, aside from affording mechanical support to the tree, is to assist in the circulation of water.

Wood fibers are narrow, elongated, sharp-pointed single cells, having very thick walls and a very small lumen. They usually have slit-like, oblique simple pits, but occasionally show small bordered pits.

Wood fibers are not found in coniferous woods, but constitute the principal source of strength, hardness, and toughness of broadleaf woods. They occur most abundantly in the intermediate portion of a ring, and attain a size varying from 0.02 to 0.10 inch in length. The fibers are usually straight and have tapered ends, but sometimes they become distorted and interwoven, or the ends may be forked or saw-toothed. This produces a wood of irregular grain which is extremely tough and offers great resistance to splitting.

Parenchyma are elements made up of rows of thin-walled cells joined end to end. They resemble wood fibers except for the presence of cross-walls (which are as thick as the side walls), and the shape of the pits, which are rounded simple pits instead of slit-like oblique, simple pits. Occasionally, as in most oaks, the cross-walls form small chambers, each of which contain a single crystal, usually of calcium-oxalate. Parenchyma fibers are found in all classes of woods, both in the vertical direction and the horizontal (in the rays). In broad-leaved woods they may be scattered throughout the growth rings (comprising the periphery of the growth ring), ranged in tangential or radial bands, or ranged around the large vessels. In the wood of the conifers parenchyma are called *resin cells*. Sometimes their arrangement is scattering, sometimes in concentric zones, and sometimes they occur in groups, especially around resin ducts.

The chief function of the parenchyma is the distribution and storage of elaborated food materials. In the conifers they are invariably associated with the formation and storage of resin.

The typical forms of various wood elements are shown by Fig. 324.

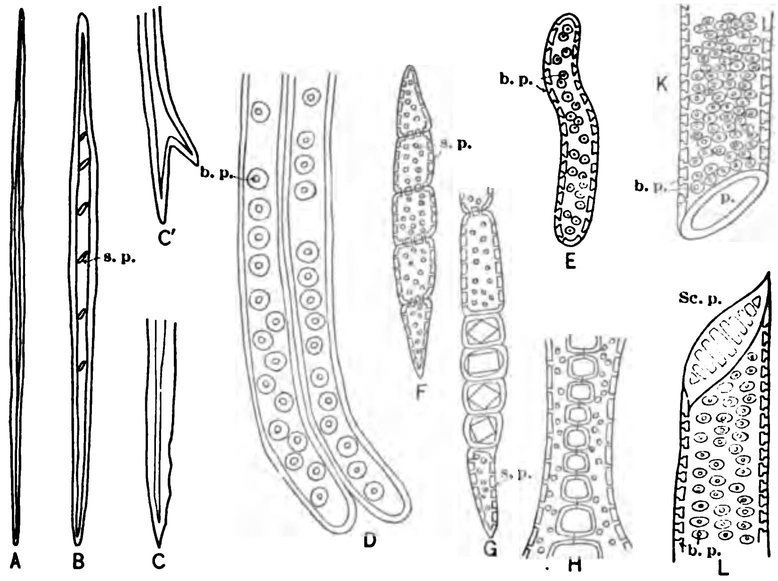


FIG. 324.—Typical Wood Cells.

A, Wood fiber with very narrow lumen; *B*, Wood fiber with large lumen showing oblique, slitlike simple pits (*s.p.*); *C*, End of wood fiber showing saw edge; *C′*, End of wood fiber showing forked structure; *D*, Ends of two tracheids from *Pinus* showing numerous bordered pits (*b.p.*); *E* , Tracheids from *Quercus; F*, Wood parenchyma fiber showing individual cells and simple pits (*s.p.*); *G*, Chambered wood-parenchyma fibers from *Juglans* showing crystals of calcium oxalate; *H*, Conjugate parenchyma cells; *K*, Portion of vessel segment showing simple perforation (*p*); *L*, Portion of a Vessel segment showing scalariform perforation (*Sc. p.*). (Record.)

562. Rays, Resin Ducts, and Pith Flecks. *Rays*, often called *medullary rays* or *pith rays*, are radial, horizontal lines or bands of cells which cross the growth rings at right angles. Those which originate in the pith are called *primary rays*, while those which have originated in the cambium at any point are known as *secondary rays*. All rays are continuous from their origin into the bark. Rays consist of radial series of cells, usually elongated horizontally, but sometimes elongated vertically in certain broad-leaved woods. In conifers the rays are for the most part only one cell wide and not more than twenty cells high, but in the resin-bearing conifers like the pines, spruces, larch, and hemlock, they may contain resin ducts and be several cells wide. Such rays are called *fusiform rays*. (Fig. 325.) In the broad-leaved woods the rays vary from one or two cells in width to very large rays, 25 to 75 cells wide and several hundred cells high (amounting to an inch or more sometimes, Fig. 326). In the coniferous woods the rays are composed largely of parenchyma, but several species, particularly the resin-bearing ones, show ray tracheids composing at least the upper and lower rows of cells, their presence being made evident by the bordered pits in their walls. In broad-leaved species the rays are composed wholly of parenchyma. The ray parenchyma are provided with simple pits in their side walls and particularly in their end walls. The principal function of the rays is the lateral distribution of plant food.

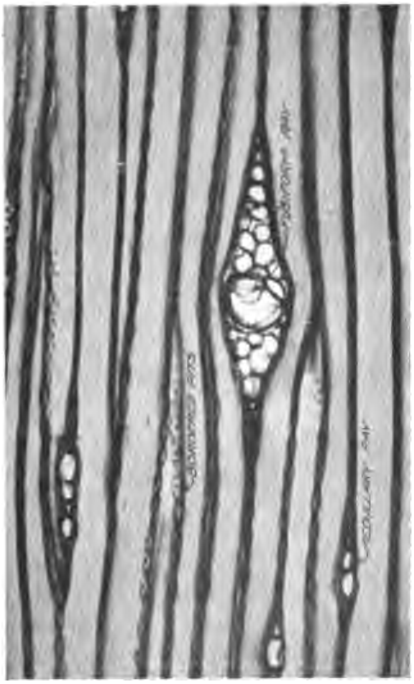


FIG. 325 —Tangential Section of Shortleaf Pine Showing Rays. (Magnification 125 Diameters.) (Bull. 101, U. S. For. Ser.)

Resin ducts are simply long, narrow, intercellular channels surrounded by parenchyma or resin cells. Unlike the vessels, they have no walls of their own. Resin ducts are common only to resin-bearing trees and usually occur particularly in that portion of the growth rings between the early and late wood, Fig. 327. The average diameter of the larger resin ducts is about 0.01 inch. Besides the large resin ducts which extend vertically, other smaller ducts are found running horizontally in the larger rays, and the two series are united at frequent intervals. Abnormal resin ducts may be developed as the result of injury, and in the case of the long-leaf pine the outer layers of the sapwood are intentionally so chipped as to form inclined ducts through which the resin may be collected and tapped. This is the source of most of the turpentine of commerce.

Pith flecks, or *medullary spots*, Fig. 328, are small, brown, crescent-shaped patches appearing on the cross-sections of certain woods, especially the birches, the maples, cherry, poplar, willow, etc. The origin of pith flecks is pathologic, they being caused by the work of the larvæ of certain insects. These insects deposit their eggs in the bark of the smaller branches and the larvæ subsequently develop in the cambium layer. In the early part of the growing season the larva travels downward in search of food, leaving a channel or mine which extends through the cambium to the base of the tree. The larva then doubles back, and for the next few weeks mines back and forth, seldom going more than 10 feet above the ground. By the middle of the summer it travels into the roots and thence presses out into the soil.

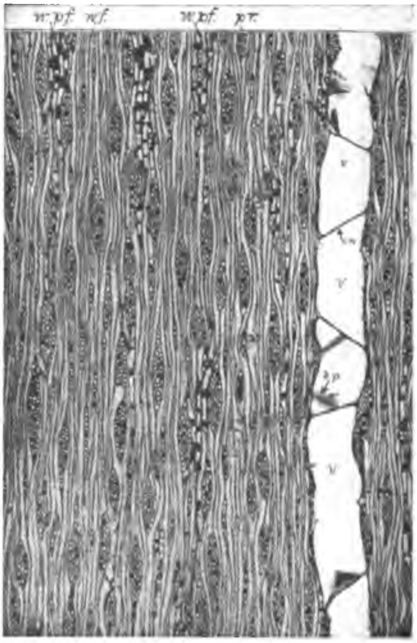


FIG. 326.—Tangential Section of Circassian Walnut. (Cir. 212, U. S. For. Ser.)

v, vessel; *p.r.*, pith ray; *w.f.*, wood fibers; *w.p.f.*, wood-parenchyma fibers; *c.w.*, cross wall; *b.p.*, bordered pits. Magnified 30 diameters.

The passage of the larva destroys those cells in its immediate path and at first the mine is scarcely more than 0.05 inch wide. As the larva grows the mine is widened until it may finally be 0.1 or 0.2 inch in the circumferential direction. It rarely occupies the entire thickness of a growth ring, since the larvæ begin their operations after the beginning and leave before the end of the growing season. The cambium becomes united again toward the periphery of the growth ring and the mine is left behind in the annual ring. The passage thus left independent of the cambium soon becomes filled with new cells similar in character to those in the rays, this action being due to the formation of *wound tissue*. The remains of dead cells and excrement of the leavæ are responsible in most cases for the discoloration of the pith fleck. Occasionally pith flecks cause disintegration of surrounding normal cells and thus give rise to intercellular spaces.

Pith flecks often render lumber unfit for certain uses by marring the beauty of its grain and, in the case of the cherry, by seriously impair-

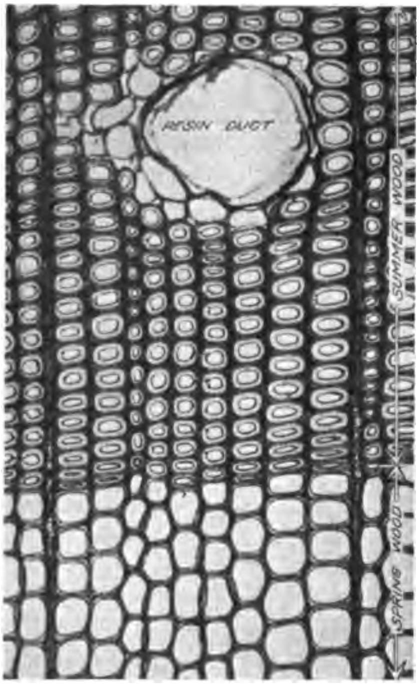


FIG. 327.—Transverse Section of Shortleaf Pine Showing Resin Duct. (Magnification 125 diameters.) (Bull. 101, U. S. For. Ser.)

ing its quality owing to the disintegration of the adjoining woody tissue. Where a pith ray encounters a pith fleck its course is abruptly terminated and the physiological activities of the tree are thereby interfered with, sometimes resulting in the surrounding wood becoming darkened prematurely as heart wood.

563. Annual Growth Rings. Spring and Summer Wood. The growth of all exogenous trees has been above explained as a process of formation of new wood fiber between the old wood and the inner bark, through the agency of the cambium. Owing to the inability of trees to sustain their physiological activities indefinitely, and the effect of the alternation of seasons in all temperate zones, this growth is intermittent, and the zones of growth correspond to the annual periods. The succeeding rings of growth may easily be distinguished from one another in most species because of the different structure of the wood formed rapidly in the spring and that more slowly added in the summer. (No wood is added during the winter months.) The distinction between adjoining growth rings is sometimes augmented by the deposition of infiltrated pigments or resin in the late wood. Thus it happens that the age of most trees may be accurately determined by counting the annual rings on a section of the stem.

FIG. 328.—Tangential Section of Silver Maple, Showing Pith Flecks. ½ Natural Size. (Cir. 215, U. S. For. Ser.)

The difference in appearance between the spring wood and the summer wood is occasionally so marked as to make the two appear as distinct bands within a single annual ring, as in the species commonly called, collectively, hard or yellow pine. More commonly, however, the spring wood merges gradually into the summer wood, and the only sharp line of demarkation is between the summer wood of one season and the spring wood of the following season. The structural difference between spring wood and summer wood may consist (1), in either an abrupt or gradual reduction in the number or the size of vessels in the later wood, e.g., oaks, chestnut, ash, locust, etc., show an abrupt change and are called "ring porous," Fig. 329, while other broad-leaved woods like maple, walnut, beech, birch, etc., show only a gradual change and are called "diffuse porous," Fig. 330; (2) in a change in the kind of wood elements, e.g., where vessels are absent from the later wood, being replaced by wood parenchyma or tracheids; or, (3) where the cell walls of the various wood elements become thicker as the season progresses, the lumen becoming correspondingly smaller and the wood more dense. This structure is characteristic of white pine, spruce, etc., Figs. 327, 331, 332, 333.

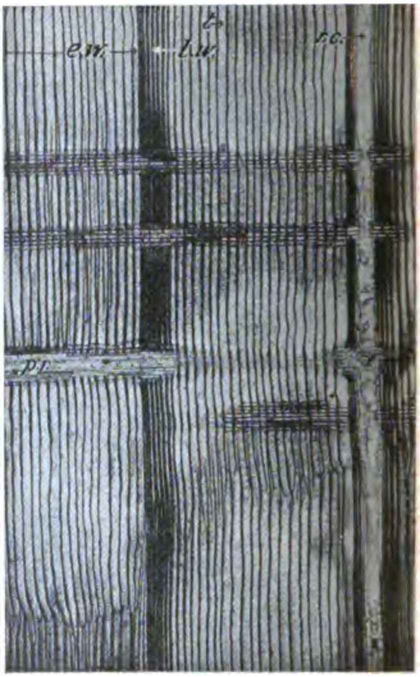
Fig. 329.—Cross-section of Ring-Porous Wood. (Red Oak). (Bull. 126, U. S. For. Ser.)

Fig. 330.—Cross-section of Diffuse-Porous Wood. (Hard Maple.) (Bull. 126, U. S. For. Ser.)

It is a commonly observed fact that the rate of growth of trees is quite variable, not only in different species, but even for different specimens of the same species. This means that the growth rings are of variable thickness. When the conditions of soil, light, heat, moisture, etc., are such as to produce normal thrifty growth, the width of the rings is greatest near the pith, decreasing outward, and it is also normally greater at the base of the stem, decreasing upward. Unfavorable soil or climatic conditions, or unfavorable seasons, will disturb the normal regularity of growth, however, and the cross-section of the stem therefore presents a history of the growth in succeeding favorable and unfavorable seasons. The thickness of the ring is not even uniform circumferentially, because of unequal acceleration of the growth on different sides; thus the section often becomes oval and, even if circular, the pith is eccentric (Fig. 334).

Fig. 331.—Transverse Section of Norway Pine. Magnified 25 Diameters. (Bull. 139, U. S. For. Ser.)

e.w., early wood; *l.w.*, late wood; *t.*, tracheids; *p.r.*, pith ray; *r.c.*, resin canal.



G. 332.—Radial Section of Norway Pine. Magnification 25 Diameters. (Bull. 139, U. S. For. Ser.)

e.w., early wood; *l.w.*, late wood; *t.*, tracheids; *p.r.*, pith ray; *r.c.*, resin canal in pith ray; also a longitudinal canal.

The maximum thickness of growth rings attained during the period of thriftiest growth rarely exceeds 0.5 inch for either conifers or broad-leaved trees. For most trees a thickness of 0.10 inch to 0.15 inch indicates a good thrifty growth, and, for trees grown under unfavorable conditions, as well as for the outer wood of very old trees the ring thickness may not exceed 0.005 inch to 0.02 inch. Trees grown in dense forests always grow less rapidly than trees grown in the open, and the growth is apt to be less rapid (the rings thinner) at the base of the stem than farther up. (Note that this is a reversal of the normal habit of growth.)

In most of the conifers the distinction between spring wood and summer wood is due to a thickening of the walls of the tracheid cells and a flattening of the cells radially, resulting in a greater density in the summer wood. The proportion of summer wood in a growth ring is normally least in the wood of the sapling, greatest in the intermediate period of thrifty growth of the tree, and falls below the average again in old age. It should average 40 to 50 per cent of the wood near the base of the stem, and falls slightly below this average at the base of the limbs. The proportion of summer wood largely determines the heaviness, strength, and structural value of the wood.

FIG. 333.—Tangential Section of Norway Pine. Magnification 25 Diameters. (Bull. 139, U. S. For. Ser.)

t., tracheids; *p.r.*, pith rays; *r.c.*, resin canal in pith ray.

FIG. 334.—Transverse Section of the Stem of a Young Balsam Fir Tree, Showing Annual Rings of Growth, *a. r.* ½ Natural Size. (Bull. 55, U. S. For. Ser.)

In most of the broad-leaved trees the distinction between spring and summer wood is largely due to a diminishing in the space occupied by vessels, and the summer wood is again the denser, heavier, and stronger portion of the wood. Unlike most coniferous woods, however, the ring-porous broad-leaved woods form their densest and strongest wood during the period of most rapid growth. This fact is due to a difference in character of the wood elements formed under different conditions of growth. When growth is most rapid, and the rings therefore widest, the middle portion of each ring contains a great abundance of the thick-walled, strong, and tough wood fibers. When the rings become narrower, it is at the expense of these wood fibers, whose strength-giving qualities cannot be equaled by the thin-walled vessels and parenchyma present. This accounts for the general preference for " second-growth " hickory, ash, etc., which has grown in less dense forest than the virgin timber, and whose growth has therefore been more rapid.

564. Sapwood and Heartwood. As the process of formation of annual rings of new wood adds layer after layer of vigorous healthy tissue over that previously formed, the latter gradually ceases to take an active part in the physiological activities of the tree, loses its protoplastic contents, and dies. Decay does not usually follow immediately, however, and the dead wood continues sound and provides mechanical support for the tree.

The living elements of the tree are called " sapwood " and the dead elements " heartwood." There is usually a sharp line of demarkation between the sapwood and heartwood, although the vigor of the living wood decreases progressively from the cambium inward. The proportion of sapwood varies considerably in different species and also between individuals of the same species. Certain woods such as maple, ash, beech, hickory, etc., usually form thick sapwood, while the juniper, the catalpa, the locust, the yew, and many others, normally form thin sapwood. Since the sapwood zone is the outer one, it forms a considerable percentage of the volume of the wood. The normal percentage of sapwood in the hickory, for instance, is about 75 per cent; in the maple, ash, beech, etc., it exceeds 50 per cent; while in the juniper, catalpa, yew, etc., it does not usually exceed 25 per cent, and in the case of the locust may not amount to more than 15 per cent. Within the same tree the percentage of sapwood usually decreases from the base upward and is least in the branches. All young trees show a higher percentage of sapwood than do old trees of the same species.

The distinction in color between sapwood and heartwood, which is characteristic of most woods, is due to the darkening of the dead wood by the presence of infiltrated pigment, gums, resins, etc., which permeate the cell walls and sometimes also the cellular and intercellular cavities. Certain woods, like spruce, fir, hemlock, poplar, willow, gum, etc., show little or no difference in appearance between the two portions.

As a rule, the heartwood is more highly valued than the sapwood of the same variety. Important exceptions, however, are the hickory, the ash, the birch, all the paper-pulp woods, and timber to be impregnated with preservatives, where the sapwood is considered preferable.

ENDOGENOUS GROWTH OF WOOD

565. Endogenous Growth. The general features of endogenous growth have been indicated above in Arts. 555 and 558. Any detailed consideration of the growth and structure of endogens (monocotyledons) is not justified, because of the relative economic unimportance of trees of this class as sources of structural timber.

The elements of the wood of endogens are similar to those of exogens, but their disposition and arrangement are radically different. The vascular bundles found in endogens are not grouped in concentric circles, but are scattered throughout the volume of the wood, each one being isolated from neighboring ones by thin-walled tracheary cells which form a pith which offers little resistance to the growth of the bundles. The bundles are not even parallel to the stem in most cases, but each one curves inward in a vertical plane (from the point where it entered a leaf), and then outward again, thus crossing many other bundles and making the structure more complex. Usually the development of new tissue is more rapid at the periphery and in the outer zone of the stem than in the interior. This results in the production of much more dense tissue toward the exterior, the solidity of the wood decreasing from the circumference toward the center. Often, when the growth is very rapid, sluggishness on the part of the interior fiber causes it to become ruptured and the enlargement of the cavity finally produces the hollow stem characteristic of the bamboo and many grasses, but not of the palms, yuccas, etc., which have a pithy center. The occurrence of knots or joints at frequent intervals is common to many endogens, particularly those which form a hollow stem. The knots mark the places whence leaves have emerged.

STRUCTURE OF WOOD OF EXOGENS

566. Structure of Wood of Conifers. The characteristic structure of coniferous woods or gymnosperms, Figs. 327, 331, 332, 333, 334, is very simple and uniform, consisting almost wholly of tracheids, resin ducts, and small parenchymatous rays. The tracheid cells are usually arranged in straight radial rows and form the great bulk of all the wood. The uniformity of this structure is disturbed only by the resin ducts, which are scattered through the summer wood portion of each annual ring, and by the rays which are small and composed usually of parenchymatous cells.

Conifers contain no vessels, and pores therefore do not appear on the section; wood fibers are wholly absent and parenchyma occur only around the resin ducts and in the rays. The tracheids have thin walls and large lumen in the spring wood, but become thick-walled and flattened radially in the summer wood, the lumen being therefore much reduced in size.

567. Structure of Wood of Broadleaf Trees. The structure of the wood of broadleaf trees or dicotyledons, Figs. 326, 329, 330, is very complex as compared with that of the conifers. This is due principally to the greater diversity of elements present, and to the presence of numerous and very large rays. Vessels are numerous in the wood of practically all dicotyledons and pores are usually prominent in the cross-section of the early wood, causing the spring wood to appear darker than the summer wood. Tracheids in broadleaf wood are always subordinate elements, and often are found only in the immediate vicinity of vessels or not at all. There are no tracheids in the rays of dicotyledons. Wood-fibers are common and constitute the principal source of strength and toughness in most broadleaf woods. They are invariably most abundant in the median portion of a growth ring and particularly in the rings of the greatest width. Parenchyma fibers are present in the wood of practically all dicotyledons and are often very prominent. Various common arrangements of the parencyhma fibers have been noted above in Art. 561. The rays of dicotyledonous woods are composed wholly of parenchyma and are, as above noted, often large and conspicuous.

PHYSICAL CHARACTERISTICS OF WOOD

568. Grain and Texture of Wood. The physical appearance of wood, so far as that is dependent upon the character and arrangement of wood elements, the width of the growth rings, etc., is described by the common terms "fine grained" and "coarse grained," "even," "smooth," or "straight grained," and "uneven," "twisted," or "cross grained," and, in a few instances, by the less common terms "curly," "mottled," "birds-eye," etc. Woods are *fine grained* if the growth has been slow, resulting in narrow rings; *coarse grained* if the rings are wide. If the main wood elements of a tree run parallel to its axis the log will be *straight grained;* often, however, the fibers follow a spiral course around the tree, producing a log of *twisted grain.* Sometimes the fibers may be oblique in one direction for several years' growth, and then become oblique in the opposite direction for a time, producing a log of *cross-grained* timber. When a straight-grained log is sawn, either straight-grained or cross-grained timber may be obtained, depending upon the parallelism of the plane of cutting and the axis of the log. Straight-grained lumber may be obtained from a log of twisted or cross grain only by splitting, lumber cut parallel to the axis being inevitably cross grained.

When the layer of wood newly formed beneath the bark becomes pitted or marked by prominences, due perhaps to the presence of dormant buds, these depressions or elevations may persist for several years, resulting in the production of the beautiful effects known as " birds-eye " marking when boards or veneer are cut tangentially. The maple has a special tendency to preserve the contour of the growth rings for many years, and bird's-eye markings and curly grain are more often encountered in maple wood than in most other woods, wherein the tendency to compensate for inequalities is strong and accidental elevations or depressions in the growth rings do not persist more than two years.

The term " texture " as applied to woods refers to the size, character, and arrangement of the wood elements in so far as they affect the structural characteristics of the wood. *Coarse texture* and *fine texture* are terms applied to woods having many large elements (particularly if many large pores are present), and to woods wherein the opposite condition prevails, respectively. The texture is *even,* or *uniform,* if the wood elements show little variation in size, and *uneven* if the contrary is true. The characteristic wood of the redwood tree and coffee tree, for instance, is coarse textured, while that of the juniper, poplar, willow, etc., is fine textured. The bald cypress, the juniper, the redwood, etc., are even textured, while all ring-porous woods like oak, ash, elm, and all woods with very different early and late wood like Southern long-leaf pine, Douglas spruce, etc., are uneven textured.

Knots originate in the timber cut from the stem or branches of a tree because of the encasement of a limb, either living or dead, by the successive annual layers of wood. Most limbs originate at the pith of the stem, and the knots found deep in a log are therefore small, increasing in size toward the bark. So long as the limb is growing, its layers of wood are a continuation of those of the stem. But a majority of the limbs die after a time, and, if a portion of a dead limb is subsequently encased by the growing stem, there will be no intimate connection between the new stem wood and the dead wood of the limb, and a board so cut as to intercept this portion of the log will contain a *loose knot.* A board cut from the log at such a depth that the limb is intercepted at a point where it was encased while still living will contain a *sound knot*, unless the knot has rotted, become badly checked, or contains a large pith cavity. A sound knot is usually harder than the surrounding wood and in coniferous woods is apt to be very resinous. On this account it may constitute a defect because of its non-retentivity of varnish or paint. Otherwise it constitutes a defect only on account of the disturbance to the grain and difficulty caused in working, or, in the event of its occurrence on the under side of a timber used as a beam, a weak point exists owing to its small resistance to tensile stress. A knot constitutes an impedance to the splitting of timber, since the fibers of the stem wood above a limb bend aside and pass around the limb while the fibers below run continuously into the limb. Thus it happens that a cleft started above a limb will never run into a knot, but one started below is very apt to do so.

569. Color and Odor. Color is a great aid to the identification of species and variety, and, within a given variety, often constitutes an important criterion of quality. New wood is practically colorless, but becomes yellowed after a few years and, except in the cases of those species which do not form a distinctive heartwood, a decided deepening of color occurs when the wood ceases to take an active part in the life processes of the tree. The sapwood of practically all species shows no great variation from the characteristic light yellow, but the heartwood shows great variation, distinctive colors being characteristic of a given species or variety. The following enumeration of a few common woods illustrates the wide variation in colors characteristic of the heart wood:

Creamy white	Holly, buckeye
Yellow	Papaw, sumac, osage orange
Dark brown	Black walnut, sweet gum
Brownish-red	Redwood, cedar
Yellowish-white	Tulipwood, poplar
Light brown	White oak, chestnut
Red-brown	Red oak, red ash
Black	Persimmon

In many instances the color is uniform, as in the wood of the walnut, the oaks, the chestnut, the elm, the redwood, the cedar, the holly, the buckeye, etc. In other cases the color is variable, as in the wood of the sweet gum, the rich brown of which is streaked and mottled with black, the tulip wood, which varies from a deep greenish yellow to brown, the blue ash, which is light yellow with brown streaks, and the osage orange, whose yellow wood is richly streaked with orange and red.

Deep color is, as above explained, always due to the infiltration of resins, pigments, tannin, etc., which, as a rule, possess an antiseptic nature and so contribute to the durability of the wood. In most instances, therefore, deep color in a specimen of a given variety is an indication of greater durability than characterizes lighter colored specimens, particularly the sapwood, of the same variety.

Dark colors are usually desirable in woods used for cabinet purposes and interior finish, and such woods are very commonly artificially darkened by the use of a filler containing Vandike brown or some other pigment. Many woods also are often stained to imitate more valuable cabinet woods, a familiar example of which is the use of birch or white mahogany stained to resemble red mahogany. All woods darken with age upon exposure, and some, like the cherry and mahogany, darken very appreciably. On this account the natural color of woods can only be observed on newly cut sections. All woods darken, some to an extreme degree, upon immersion in water.

The odor of wood, like the color, is due not to the wood itself, but to the foreign chemical compounds present. It is therefore usually more pronounced in heartwood than in sapwood, and is less pronounced after exposure than when wood is freshly cut. Sometimes the odor of green wood is entirely lost upon exposure, and, in some instances (e.g., the oaks), a new and often disagreeable odor is acquired, owing to the decomposition of organic compounds present.

All woods possess a characteristic odor in some degree, although it is not readily perceptible. Pines have a marked resinous odor; cedar has a strong aromatic or spicy scent which persists for many years, and which is valued because it is offensive to certain insects which attack woolen goods, furs, etc.; bald cypress possesses a rancid odor; catalpa smells somewhat like kerosene; and many other species such as the juniper, arbor vitæ, hemlock, sassafras, camphor-tree, etc., possess well-known distinctive odors which are not easily described.

Decaying timber usually possesses a strong odor which may be very disagreeable, as in the case of the poplar, or fragrant, as in the case of decaying red oak. The odor of green wood, seasoned timber or decaying timber often provides an infallible indication of species.

570. Density and Weight. The density of woods of different species, different individuals of the same species, and even portions of the same individual, varies considerably, owing to differences in structure (particularly, differences in the average thickness of cell walls), and to differences in the amount of water present in the cells and cell walls. The specific gravity of the ultimate wood fiber of all species, however, is about 1.6, so that it is apparent that no wood would float in water were it not for the buoyancy of the air present in the cells, walls, and intercellular spaces.

In all varieties of trees the sapwood is heavier than the heartwood because of its greater water content, and the summer wood is heavier than the spring wood because of the smaller lumen and thicker walls of the cells of the late wood. A fiber from the dense summer wood of such a tree as the long-leaf pine will not float, regardless of its water content, and many woods will not float while still very green. Even seasoned timber of many species may be made to become " water-logged," i.e., a large part of the imprisoned air displaced by water.

Within a single tree of a given species specimens taken from different portions of the stem and branches exhibit wide variation in weight. All trees form their heaviest wood at the butt and at the base of the limb (knots), and the weight decreases toward the upper portion of the stem and the tips of the branches. If the weight of the several zones of wood formed during successive periods of growth be compared, it will be found again that the weight varies considerably, the manner of variation being fairly constant for all specimens of a given species grown under normal climatic and soil conditions, but differing between species of radically different habits of growth. Two factors chiefly influence the weight of wood formed at succeeding periods of growth: first, the proportion of summer wood formed, and second, the size and number of pores present in the early wood. The first is the controlling factor in the case of most conifers, and such trees as pine, spruce, etc., form light wood as saplings when the proportions of early wood is greatest, the heaviest wood during the period of thriftiest growth when summer wood preponderates, and lighter wood again in old age when the proportion of summer wood drops below the maximum. In most dicotyledons, on the other hand, especially those whose pores are conspicuous, like the oak, chestnut, ash, etc., the heaviest wood is that of the sapling and the wood becomes slightly lighter with each succeeding year's growth. This is due to the fact that the pores in the wood near the pith are very minute, but larger and larger pores are formed during succeeding periods of growth.

The weight of wood is in itself an important quality in many of its applications to structural uses. Weight is also closely related to strength, providing the disturbing factor of variation in moisture content is eliminated, so that, at least within a given species the relative strength of different specimens are directly proportional to their weights.

The weight of wood is experimentally determined by subjecting thin discs of the wood to an oven temperature of 100° C., till they cease to lose weight by evaporation of moisture. Taking into account the considerations above discussed, it is evident that the results of experimental determinations will be extremely variable, and the value usually assigned to a given species is simply the average of a large number of tests Such a value has only a general application, and especially so because the moisture content of lumber is variable and always amounts to at least 8 or 10 per cent unless the lumber is kept in a dry-kiln.

The following table, abstracted from the Tenth Census of the United States, gives an approximate idea of the relative specific gravity and

FIFTY TREES OF THE UNITED STATES, ARRANGED IN ORDER OF AVERAGE SPECIFIC GRAVITY

(Abstract from 10th U. S. Census)

Common Name.	Gen. Class.	Approx. Sp.gr.	Approx. Wt. Lbs. per Cu.ft.	Wt. Class.
Lignum vitæ	Broad leaf	1.14	71	Very heavy
Live oak	"	.95	59	"
White hickory	"	.84	52	"
Pignut hickory	"	.82	51	"
Osage orange	"	.77	48	"
Cuban pine	Conifer	.75	47	"
White oak	Broad leaf	.75	47	"
Locust	"	.73	46	"
Blue beech	"	.73	46	"
Mahogany	"	.73	46	"
Cedar elm	"	.72	45	"
Blue ash	"	.72	45	"
Pecan hickory	"	.72	45	"
Long-leaf pine	Conifer	.70	44	"
Slippery elm	Broad leaf	.70	44	"
Sugar maple	"	.69	43	Heavy
Beech	"	.69	43	"
Yellow birch	"	.66	41	"
White ash	"	.65	40	"
Red oak	"	.65	40	"
White elm	"	.65	40	"
Red ash	"	.63	39	"
Tamarack	Conifer	.62	39	"
Black walnut	Broad leaf	.61	38	"
Short-leaf pine	Conifer	.61	38	"
Paper birch	Broad leaf	.60	37	"
Sweet gum	"	.59	37	Medium
Western juniper	Conifer	.58	36	"
White birch	Broad leaf	.58	36	"
Sycamore	"	.57	36	"
Loblolly pine	Conifer	.54	34	"
Douglas spruce	"	.52	32	"
Red juniper	"	.49	31	"
Bull pine	"	.47	29	Light
Red fir	"	.47	29	"
Black spruce	"	.46	29	"
Bald cypress	"	.45	28	"
Basswood	Broad leaf	.45	28	"
Chestnut	"	.45	28	"
Catalpa	"	.45	28	"
White basswood	"	.43	27	"
Hemlock	Conifer	.42	26	"
Redwood	"	.42	26	"
Butternut	Broad leaf	.41	26	"
White spruce	Conifer	.41	26	"
Incense cedar	"	.40	25	"
White pine	"	.38	24	Very light
Balsam fir	"	.38	24	"
White fir	"	.36	22	"
Cork wood	Broad leaf	.21	13	"

weight of fifty of our most important lumber woods. The limited application of these average values should be remembered, and their use confined largely to the comparison of particular specimens of equal moisture content, and to a general classification of woods as very heavy, heavy, medium, light, and very light. The weight classification here given is that adopted by Roth.*

571. Moisture Content of Wood. Water occurs in the sapwood of living trees in three states: (1) It forms more than 90 per cent of the protoplasmic contents of the living cells, (2) it saturates the cell walls, (3) it partially or entirely fills the lumina of empty lifeless cells, fibers and vessels. The heartwood water occurs only in the second state, i.e., it exists in the cell walls. As a typical illustration of the distribution of water, Roth states that in the fresh sapwood of white pine water comprises about one-half of the total weight, distributed about as follows: 5 per cent in the contents of living cells; 35 per cent in the cell walls; 60 per cent in the lumina of empty cells.

The highest percentage of water is found in the wood near the bark, decreasing gradually toward the pith unless heartwood is formed, in which latter event, an abrupt decrease in the moisture percentage occurs at the heartwood limit. From the above considerations it will be apparent that, in the case of trees which do form heartwood, the moisture content at any section will vary with the proportion of sapwood, and is therefore greater in the upper than in the lower portion of the stem, still greater in the limbs, and greatest of all in the roots.

It is impossible to determine the percentage of water in wood experimentally. For practical purposes, however, wood is considered thoroughly dry when a thin cross-sectional disc ceases to lose weight in a constant temperature of 100° C. At higher temperatures additional water will be given off, but chemical destruction sets in before all the water is driven off.

572. Seasoning of Timber. The seasoning or drying of timber necessarily precedes its application to structural purposes. The natural drying of timber by long outdoor exposure to the action of the air is called "seasoning," while artificial drying by exposure for a limited period to high temperatures in a closed chamber is called "kiln-drying." In either event the loss of moisture is entirely by evaporation, and the treatment is appreciably beneficial to strength, stiffness, and durability.

The rate of drying of timber depends upon the dimensions of the piece and the structure of the wood. Thin boards dry much more rapidly than thick planks or heavy timber, and light porous woods much more rapidly than heavy dense woods. Moisture evaporation from the cross-

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* Bulletin 10, Forestry Division, U. S. Department of Agriculture.

section of porous wood is, at first, very rapid, that from the radial section very much less rapid, and that from the tangential section still less rapid. The total moisture evaporation from these different sections in a given time will bear this relation one to the other, however, only when equal areas are exposed on each section. This is due to the fact that drying proceeds inward from any section at a rapidly diminishing rate. Numerous experiments made by Mr. H. S. Betts of the U. S. Forest Service upon large timbers of loblolly and long-leaf pine established the following conclusions: *

" (1) The drying-out process takes place almost wholly through the faces of the beams and not longitudinally, except near the ends.

" (2) The rate of evaporation through a surface is proportional to the rate of growth or density of the wood near the surface, being most rapid in case of the sapwood.

" (3) If the whole stick is made up of heartwood or the proportion of sapwood is uniform throughout, the longitudinal distribution of moisture is very regular. If the proportion of sapwood is not uniform, on the other hand, the portion containing the most sap is the most susceptible to moisture influences, i.e., it will dry or will absorb the moisture the most rapidly.

" The average of two cross-sections of long-leaf pine sticks, 12 by 12 inches and 8 by 16 inches, and 16 feet long, which were air dried for two years, showed an average moisture content in the outer portion, cut half way from surface to center, of 17.7. per cent, while the inner part contained 25.7 per cent.

" From this it is quite evident that where timber of structural sizes is used, the strength ordinarily reckoned upon should not be greater than that of the green condition."

In artificial drying temperatures of 158° to 180° F., are usually employed.† Pine, spruce, cypress, cedar, etc., are dried fresh from the saw, allowing four days for 1-inch boards. Hard woods, especially oak, ash, maple, birch, sycamore, etc., are air seasoned for three to six months to allow the first shrinkage to take place more gradually, and are then exposed to the above temperatures in the kiln for about six to ten days for 1-inch lumber. Freshly cut poplar and cottonwood are often dried directly in kilns.

By employing lower temperatures, 100° to 120° F., green oak, ash, etc., can be seasoned in dry kilns without danger to the material. Steaming the lumber is commonly resorted to in order to prevent checking and case hardening, but not, as has frequently been asserted, to enable the board to dry. Yard-dried lumber is not dry, and its moisture is too

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* Bulletin 70, U. S. Forest Service, p. 123.

† Roth, Bulletin 10.

unevenly distributed to insure good behavior after manufacture. Careful piling of the lumber, both in the yard and kiln, is essential to good drying. Piling boards on edge or standing them on end is believed to hasten drying. This is true only because in either case the air can circulate more freely around them than when they are piled in the ordinary way. Boards on end dry unequally—the upper half dries much faster than the lower half and horizontal piling is, therefore, preferable.

Since the proportion of sapwood and heartwood varies with size, age, species, and individual, the following figures must be regarded as mere approximations:

POUNDS OF WATER LOST IN DRYING 100 POUNDS OF GREEN WOOD IN THE KILN

	Sapwood.	Heartwood
(1) Pines, cedars, spruces, and firs	45–65	16–25
(2) Cypress, extremely variable	50–65	18–60
(3) Poplar, cottonwood, basswood	60–65	40–60
(4) Oak, beech, ash, elm, maple, birch, hickory, chestnut, walnut, and sycamore	40–50	30–40

The lighter kinds have the most water in the sapwood, thus sycamore has more than hickory.

573. Shrinkage, Warping and Checking in Drying. The shrinkage of wood in drying is due solely to the loss of moisture from the walls of the cells. Variation in the water content of the lumina of the lifeless cells, and in the protoplasmic contents of the living cells, does not affect the volume of the wood in any way.

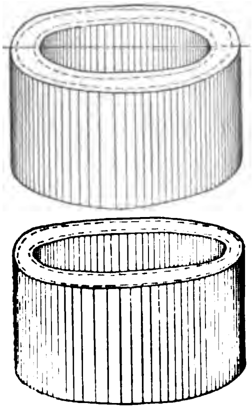

Fig. 335. — Shrinkage of thick-walled and thin-walled fibers. (Bull. 10, U. S. For. Div.)

As moisture is evaporated, the cell walls become thinner; the lumina become larger, and the exterior cross-sectional dimensions become smaller. The contraction of a wood element in a longitudinal direction is scarcely appreciable, however. The total volumetric change of an element is roughly proportional to the original thickness of its walls. The aggregate volumetric change of a mass of thin-walled wood elements is therefore much less than that of a mass of thick-walled elements, Fig. 335. This explains the fact that summer wood almost invariably shrinks more than spring wood, its wood elements being thicker walled, and dense wood shrinks more than lighter wood of the same species for the same reason.

Irregularities in the structure of all wood prevents shrinkage being uniform throughout. The rays, whose elements are for the most part arranged at right angles to the main wood elements, oppose shrinkage in a radial direction and tend to cause longitudinal shrinkage. The bands of dense summer wood are continuous in a tangential direction, but in a radial direction they alternate with less dense spring wood. On this account tangential shrinkage commonly amounts to at least twice the radial shrinkage. Longitudinal shrinkage will be greatest in woods having an abundance of large rays or those exhibiting wavy or spiral grain (the lack of parallelism of the wood elements with the pith in this case being accountable for the existence of a component of the transverse cell shrinkage in a direction parallel to the pith), but in any event the longitudinal shrinkage amounts to only a few tenths of 1 per cent.

The following table gives the results of shrinkage tests made at the Yale Forest School by Mr. H. P. Baker and quoted by Record.* The values given represent the average percentage shrinkage (original dimensions taken as a basis) in reducing green wood to a kiln-dry condition.

Wood.	Length, Per cent.	Radius, Per cent.	Circumference, Per cent.	Area of Cross-section, Per cent.	Volume, Per cent.
Red juniper	0.32	2.7	5.6	6.9	5.9
Butternut	.36	2.9	6.9	7.3	7.6
Chestnut	.25	3.0	4.9	11.2	
Red oak	.24	3.7	8.2	10.4	
Tulip tree	.15	4.3	9.3	12.6	13.7
Black gum	.10	6.1	11.5	17.1	18.0
White hickory	.04	7.4	9.2	19.4	19.8

The warping of lumber is due either to unequal drying of different portions, or to unequal shrinkage on account of irregularities in structure. Any straight-grained green board exposed on one side only to air and heat will become concave on the exposed side because of the more rapid drying and consequent shrinkage of that side. Boards cut tangentially from the log tend to become convex on the side toward the pith when dried, because of the greater shrinkage of the wood in a direction parallel to the annual growth rings. (Each growth ring tends to shorten, thus causing the edges of the board to curl away from the pith as shown by Figs. 336 and 337. If lumber is cross-grained, the component of the shrinkage in a longitudinal direction causes a warping lengthwise as well as in the transverse direction, and where the grain is spiral boards may become badly twisted. Warping is always more apt to be encountered

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* "Economic Woods of the United States," p. 57.

in the lumber from woods of great irregularity. Serious deformation of such lumber can be avoided only by most careful handling in drying.

Checking of timber in drying is a consequence of the inability of the wood to accommodate strains consequent upon unequal shrinkage. A great many small checks occur, particularly in the ends of timbers, owing to the more rapid drying from the cross-section and the consequent excess of shrinkage of the end portion over that of the balance of the timber. This results in a tendency to bend the fibers, Fig. 338, and their stiffness may be sufficient to cause rupture between strands, thus relieving the stress. Similar checks occur on the sides of logs and timbers because of the precedence of the shrinkage of the outer portion over that of the inner portion, which has scarcely begun to lose its moisture. Both of these classes of seasoning checks are considered temporary, because they close up and become imperceptible as the inner portion of the timber dries and shrinks. They are still there, whether visible or not, however, and always impair the structural qualities of the wood in some measure.

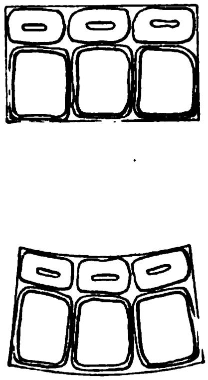

FIG. 336.—Shrinkage of Thick- and Thin-walled Fibers. Warping of Wood. (Bull. 10, U. S. For. Ser.)

Another class of checks, more important than the temporary checks, because they are apt to be larger and are permanent, are those caused principally by the greater shrinkage of timber in a tangential direction along the rings than that along the radius. The occurrence of the rays in radial planes often contributes to the formation of these large radial checks, because they form a plane of weakness at the very point where the strains are the greatest and most complex (two severe stresses existing at right angles to each other, owing to the shrinkage of the rays opposing the shrinkage of the main wood fibers). The danger of the occurrence of large checks of this nature constitutes a serious difficulty in seasoning large timbers, and especially round timbers such as poles, piles, and posts. Too rapid seasoning always increases the danger of injury by excessive checking.

Some woods, mostly hard woods, become "case-hardened" when rapidly dried in the kiln; that is, the outer part dries and shrinks, and commonly checks, while the interior is still practically in its original condition. The drying of the interior is thus retarded, but when it does occur great internal strains are set up, resulting in the formation of large or numerous radial checks which follow the rays. When these checks are comparatively small, but numerous, the wood is said to be "honeycombed." The case-hardening of timber may be avoided by air seasoning before placing it in the kiln or by occasionally admitting steam to the kiln.

Wood, when dried, has the ability to reabsorb water from the atmosphere. This property is termed "hygroscopicity." The amount of hygroscopic water thus acquired always exceeds the moisture content of the air, but varies with the humidity. The consequent shrinking and swelling of the wood is a serious hindrance to its use where exact fitting is desired. The hygroscopicity of wood may be reduced, but not eliminated, by prolonged exposure to temperatures in the neighborhood of 100° C., or by boiling, steaming, or prolonged soaking.

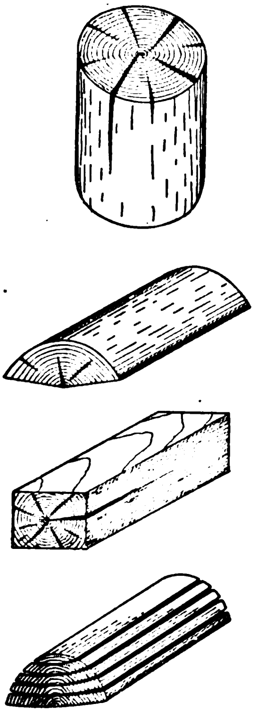

Fig. 337.—Effects of Shrinkage.
(Bull. 10, U. S. For. Div.)

Fig. 338.—Formation of Checks.
(Bull. 10, U. S. For. Div.)

The harmful effect of the shrinking or swelling of wood used in interior finishing may be minimized on the one hand by avoiding large continuous surfaces by paneling, etc., or, on the other hand, by rendering the wood more or less impervious to moisture by the use of coatings of oils, paints, varnishes, etc.

MECHANICAL PROPERTIES OF WOODS

574. General. The intelligent use of wood for any structural purpose requires a general knowledge of the mechanical properties of different woods, in order that the one selected may conform in its structural qualities to the requirements imposed, and in order that a given purpose may be served at a minimum expense.

Wood is not like many other structural materials in that its mechanical properties are extremely variable, not only between different species and different trees of the same species, but also between specimens cut from different portions of the same tree. An assumption as to the mechanical properties of certain timber of a given variety can therefore be predicated upon the results obtained in tests of timber of that variety only in a most general way, unless detailed information concerning the many factors governing the mechanical properties of both test timber and commercial timber are known. Some of these important factors are: (1) correct indentification of species and variety, (2) age and rate of growth of trees, (3) position of test specimens in the tree, (4) moisture content, and (5) relative freedom of test specimens and commercial timber from defects such as knots, checks, etc. Even if all this information is available the conclusion reached concerning the probable strength is only approximate, because the exact weight of each of the above factors has not been definitely established. We have, however, fairly definite information concerning the allowance to be made for variation in the moisture content and rate of growth.

The variation in test results for which these factors must be considered principally accountable is indicated by the following inspection of a series of compressive and bending tests of 32 species of American woods, made

Proportion of Tests within 10 Per cent of Average.						Proportion of Tests within 25 Per cent of Average.					
Minimum Proportion (One Species)		Maximum Proportion (One Species).		Average Proportion (All Species).		Minimum Proportion (One Species).		Maximum Proportion (One Species).		Average Proportion (All Species).	
Compression, Endwise. Per cent.	Rupture in Bending. Per cent.	Compression, Endwise. Per cent.	Rupture in Bending. Per cent.	Compression, Endwise. Per cent.	Rupture in Bending. Per cent.	Compression, Endwise. Per cent.	Rupture in Bending. Per cent.	Compression, Endwise. Per cent.	Rupture in Bending. Per cent.	Compression, Endwise. Per cent.	Rupture in Bending. Per cent.
28	20	79	64	56	38	65	58	100	95	93	76

In the above summary variability of results due to differences in moisture content has been eliminated by correction to a constant moisture content.

by the U. S. Forestry Division.* The number of tests of each kind made upon each species varied from 10 to more than 1200, and averaged about 180.

575. Tensile Strength. The tensile strength of timber is not an important property except in so far as the tensile strength is involved in all cases of transverse loading. Timber used in construction is practically never subjected to pure tensile stresses for the simple reason that the end connections cannot be so devised that they do not involve either shear along the grain or compression across the grain, and, since the resistance offered by any timber to compression across the grain, or shearing stress along the grain, never amounts to more than a small fractional part of the tensile strength, it is evident that considerations of economy in the design of structures will call for the use of iron or steel instead of timber for those members which must withstand tension.

Tensile tests of woods are seldom made for the reason above indicated. When they are made, the specimens must have a reduced section, the area of which is not more than about one-tenth the area of the ends which are gripped by the jaws of the testing machine or pierced by the cross-bolt of a shackle through which the load is applied.

Failure in tension across the grain involves principally the resistance offered by the thinner-walled wood elements to being torn apart longitudinally. The thin-walled parenchymatous cells and vessels are most often the determining factor. The thick-walled wood fibers are not torn, but are pulled apart. Wood sustains in tension across the grain only a small fraction (one-tenth to one-twentieth, perhaps) of the load carried in tension along the grain. The tensile strength of a number of varieties of timber woods in a direction perpendicular to the grain (tested in a green condition) are listed in Table I at the end of this chapter.

Failure in tension along the grain involves principally the resistance offered by the wood elements to being torn apart transversely or obliquely. The strands of wood elements are practically never pulled apart by failure of the union between adjacent strands or fibers. The nature of the prevailing wood elements is a factor in so far as it affects the actual area of cell walls encountered in a cross-section. A more important factor, however, is the structure of the wood as a whole, the tensile strength being especially dependent upon the arrangement of the wood elements. Cross grain is prejudicial to tensile strength, and rays, owing to their transverse position with respect to a load applied along the grain and their small resistance to tension in a direction normal to the direction of their fibers, greatly weaken the timber. Their disturb-

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* Circular 15.

ance of the normal regularity of arrangement of the main wood fibers is also injurious. Knots similarly weaken wood subjected to longitudinal tension because of the likelihood of their being either loosely connected with the adjoining wood substance, badly checked, or structurally impaired by a pith cavity.

On account of the considerations mentioned above, little experimental data are available concerning the strength of wood in longitudinal tension. The only importance of tensile strength in the direction of the grain arises from the circumstance that the lower side of a beam subjected to transverse load is obliged to withstand tensile stresses. This case will later be discussed under the head of cross-breaking strength and stiffness.

576. Compressive Strength. The compressive strength of wood in a direction normal to the grain is simply a matter of the resistance offered by the wood elements to being crushed or flattened. The cells with the thinnest walls collapse first and the action proceeds gradually, the so-called " elastic limit " being usually fairly well marked by the departure of the load-deformation curve from a straight line. A load which cannot be exceeded will be finally reached (the specimen continuing to distort without increase of load), but there is no such thing as a breaking load in transverse compression of wood.

The endwise compressive strength of wood, i.e., the strength of wood in compression along the grain, is dependent upon the anatomical structure and the moisture content of the wood, and the manner of failure is fixed by these same factors. The individual fibers (or other elements) of wood act as so many hollow columns bound firmly together, and failure involves either buckling or bending of the individual fibers or bundles of elements which finally come to act almost independently. Buckling is characteristic of any thin-walled cells when dry, as in the case of the early wood of many species, the vessels of others, and the wood of seasoned white pine, spruce, etc., as a whole. Bending is typical of all green or wet woods, and of those portions of any wood which are made up principally of thick-walled cells, whether wet or dry. The isolation of bundles of elements is very frequently caused by longitudinal splitting, which occurs by a tearing of the fibers of the wood, including those of the rays.

The presence of moisture in wood decreases the stiffness of the cell walls, and lowers the compressive strength very materially in consequence. Moisture also facilitates the separation of the fibers from one another.

From the above considerations it will be apparent that the principal factors affecting the compressive strength along the grain are: (1) the actual amount of wood substance encountered in a section, i.e., the density of the wood, (2) the strength of the union between the wood fibers or longitudinal strands of wood elements (particularly as affected by contained moisture), (3) the stiffness of the wood fibers or longitudinal strands of elements (again largely a matter of moisture content), and (4) the continuity of the course of the longitudinal strands in a direction parallel to the axis of the piece. Woods in which the separate elements are closely interlaced and bound together, without the existence of distinct longitudinal planes of weakness, such as exist in ring-porous woods, for instance, will be stronger than woods of opposite character; well-seasoned wood will be stronger than green woods, the stiffness of which is decreased by a high moisture content; and straight-grained woods will be stronger than cross-grained or knotty woods, or woods in which rays are large and abundant.

Thus we find that the strongest of our common woods in compression with the grain are the dense and tough hickories, birches, hard maple, locust, etc.; oaks, long-leaf pine, elm, ash, etc., rank next; short-leaf pines, western hemlock, beech, cedar, cypress, etc., are placed in a third division; while basswood, butternut, chestnut, hemlock, spruce, soft pines, fir, etc., are ranked among our weakest woods. Tabulations of the mechanical properties of some of the principal lumber woods of the United States will be found at the end of this chapter.

The resistance offered to crushing across the grain is dependent practically entirely upon the density of the wood, since failure can occur only by flattening of the wood elements as their lumina are closed up. The crushing strength across the grain is therefore least for the lightest, most porous woods, and greatest for the heaviest and densest woods. An inspection of the data given in Table II reveals the fact that the relation of compressive strength across the grain to compressive strength along the grain is represented by the following factors: viz., 13 to 14 per cent for white pine, cedar, cypress, and spruce, 15 to 16 per cent for the various grades of hard pine, 18 to 26 per cent for elms, 21 to 26 per cent for ash, 22 to 26 per cent for oaks, and 23 to 31 per cent for hickories.

577. Cross-breaking Strength and Stiffness. The cross-breaking strength of any material is necessarily closely related to the tensile and compressive strength of that material, since the stresses encountered in a specimen loaded transversely are principally tensile stresses in the lower portion of a beam and compressive stresses in the upper portion. There also exist certain shearing stresses, consequent upon flexure, which are relatively so small that they may be neglected in considering materials whose shearing strength is a large fraction of the compressive strength. With timber, however, the strength in shearing along the grain is so very small that these stresses cannot be wholly neglected, and it is often observed in tests of timber that the initial failure is by longitudinal shear.

It has been shown above that the tensile strength of all timbers is greatly in excess of its compressive strength (about three times as much on the average), and the latter factor will therefore usually be the determining factor in limiting the cross-breaking strength. (Compressive strength will always be the determining factor, assuming there exist no defects such as knots, uneven grain, etc., on the under side of the beam, if the load is not a single concentrated load, but is applied at several points or distributed along the beam so that the shearing stressrs are reduced to a minimum.) It is apparent, therefore, that the considerations which fix the compressive strength similarly affect the cross-breaking strength, and, in fact, there is no reason why the compressive stress in the uppermost fiber of a beam at time of failure should not be precisely the same as the ultimate compressive strength of the wood. The computed value of the fiber stress under the breaking load always greatly exceeds the ultimate compressive strength, however, because this apparent stress exceeds the actual stress. (We compute the extreme fiber stress at rupture, i.e., the modulus of rupture, by the rule $f=My/I$, which involves the assumption that the material is still behaving elastically up to actual failure and, therefore, that the fiber stress is still directly proportional to the distance of the fiber from the neutral axis. As a matter of fact, the elastic limit of the material has long since been passed when the breaking load is reached, the neutral axis has shifted, and the extreme fiber stress is no longer proportional to the bending moment.)

Although the compressive strength is always the determining factor which limits the transverse strength of wood, it is often only the initial failure which occurs in compression. The fibers on the compression side are caused to buckle or fold (slightly, at least), with the result that the neutral axis becomes shifted and the portion of the area of the section which is subjected to compression probably becomes relatively so much greater than the area subjected to tension that the intensity of tensile stress is disproportionately increased and ultimate failure in tension follows.*

The stiffness of timber used structurally as beams is often quite as important as its cross-breaking strength. In plastered ceilings, for instance, the maximum deflection permitted is usually limited to 1/360 of the span, so that timber beams must be so designed as to not only carry the load imposed safely, but also to do so without excessive deflection.

The stiffness of timber, as in the case of any material which behaves

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* This theory of transverse failure is attributed to Prof. Suenson of Copenhagen and has received some experimental verification. See Proc. Sixth Congress Internat. Assoc. for Test. Matrls., 1912, $XXIII_2$, pp. 12–17.

elastically, is most conveniently expressed by the modulus of elasticity, which quantity is computed from the expression:

$$E=\frac{(Pl^3)}{(4dbh^3)},$$

wherein P is a central concentrated load on a simply supported beam of span l; d is the deflection due to P; b is the width; and h is the height of the beam. Comparing the above expression with the similar expression for the modulus of rupture, i.e.,

$$f=\frac{(3wl)}{(2bh^2)},$$

it will be noted that, whereas the strength is proportional to the span, the deflection is proportional to the cube of the span, and, whereas the strength is inversely proportional to the square of the depth of the beam, the deflection is proportional inversely to the cube of the depth. It is evident from this comparison that the stiffness rather than the strength will often be the governing factor in selecting a timber beam for a given situation.

Stiffness of timber is largely dependent upon the same factors as strength. Dense woods are always stiffer than open, porous woods, and heavy woods are stiffer than light woods except in so far as the weight is attributable to moisture contained. Thus the wood of the long-leaf pine is stiffer than than of the white pine, and the wood of the hickory is stiffer than that of the chestnut. All woods are stiffer when well seasoned than when green, and a given timber of a variety showing distinct bands of summer wood will be stiffer if so placed that the general direction of the annual rings in its cross-section is vertical rather than horizontal. (See Tables I and II.)

578. Moisture and Strength. The important effect of moisture upon the strength and stiffness of woods has been often mentioned in the preceding discussion, but no effort has hitherto been made to show exactly what difference in strength and stiffness of a given timber is caused by a given change in moisture content.

All woods gain both in strength and in stiffness when thoroughly air seasoned or kiln dried. The actual net gain which, from a comparison of strength and stiffness of small specimens in the green and oven-dry condition, would appear to be attainable, cannot be even approximately realized in practice, however, because of the operation of several factors which greatly modify the effect of lessened moisture. Checking, for instance, always occurs to some extent in drying lumber and will partially or entirely counterbalance the gain due to drying, the extent of this effect being dependent upon the size and the variety of the timber. The general character of the effect of various moisture contents upon the

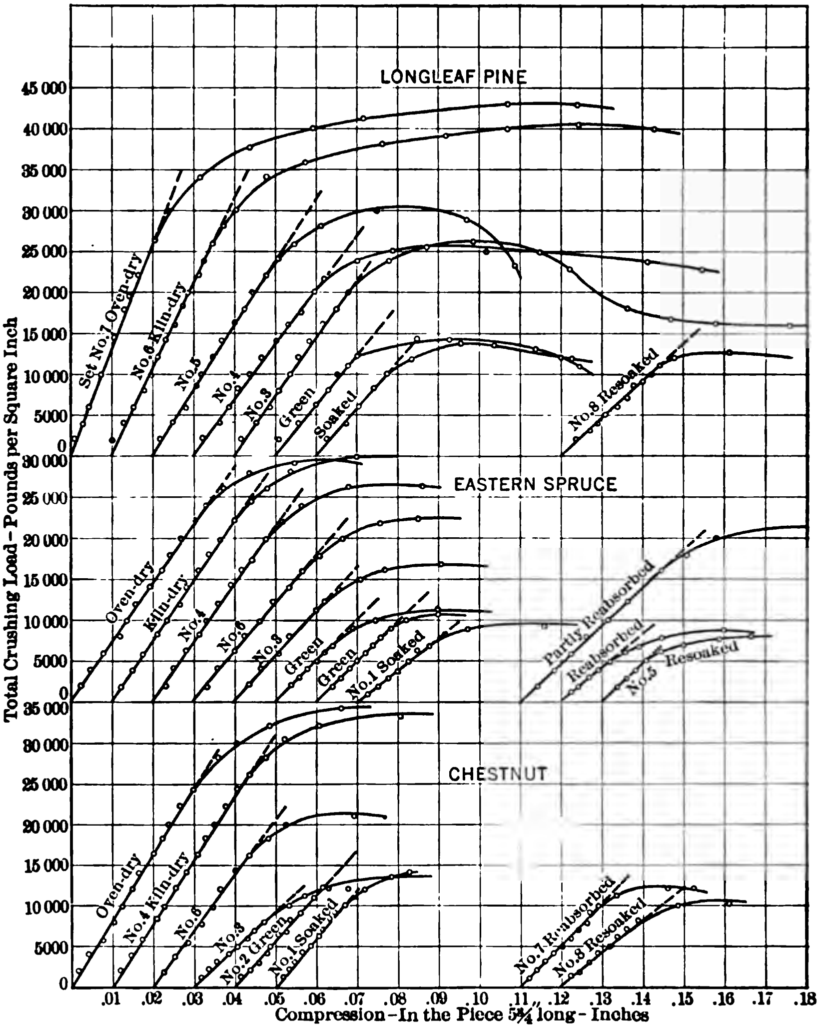

Fig. 339.—Typical Stress-strain Diagrams for Three Species of Wood, Showing the Effect of Different Degrees of Moisture upon Strength and Elastic Properties. Tested in Compression Parallel to the Grain. (Cir. 108, U. S. For. Ser.)

strength and stiffness of three varieties of timber woods is shown by Fig. 339.*

* U. S. Forest Service, Circular 108.

Large timbers dried only by air-seasoning, even though the process is prolonged for several months or even years, seldom lose sufficient moisture to benefit their strength to more than a slight degree. Such timbers, therefore, cannot be safely depended upon to show any greater strength than if they were in the original green condition. The explanation of this fact is that a great part of the moisture which is first evaporated from wood is water which exists only as " free water " in the lumina of vessels and cells, whereas only variation in the moisture content of the walls of the wood elements affects strength in any way. " The degree of moisture at which maximum absorption by the cell walls is reached is called the ' fiber-saturation point ' of the wood. After this point is reached

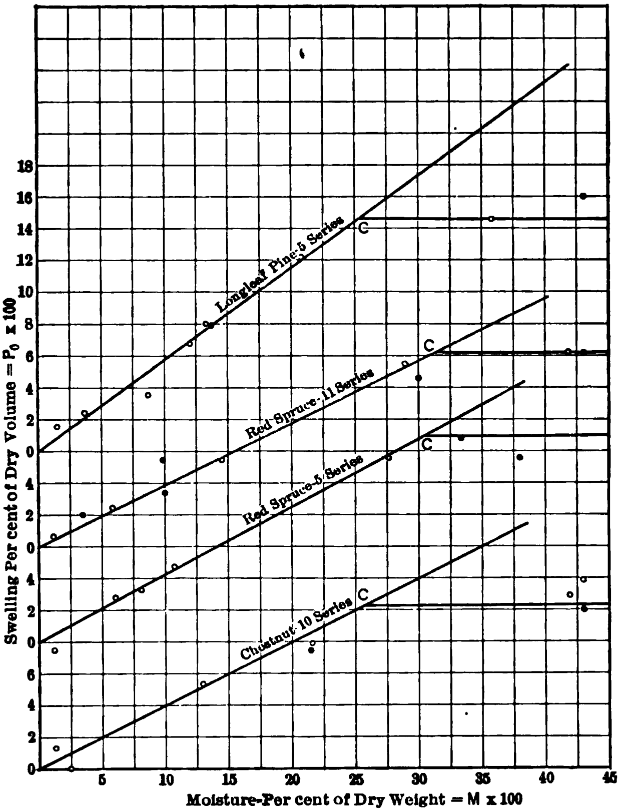

FIG. 340.—Relation between Swelling and Moisture Content. (Black Dots indicate Specimens that were Kiln-dried and then Allowed to Reabsorb Moisture.) (Cir. 108, U. S. For. Ser.)

added moisture does not lessen the strength of wood. At this point also, wood ceases to swell," Fig. 340.

The fiber-saturation point is determined experimentally by tests of the strength of very small specimens covering a large range of moisture content. When further moisture no longer lessens the strength the fiber-saturation point is reached. Tiemann found this point for various woods to be within the following limits: *

	Per cent.
Long-leaf pine	24–26
Red spruce	29–35
Chestnut	24–28
Loblolly pine (heartwood)	23–24
Loblolly pine (sapwood)	24–26
White ash	19–23
Red gum	25
Douglas fir	23
Norway pine (heartwood)	27–34
Norway pine (sapwood)	26–30
Tamarack	27–33

(See Fig. 340.)

Experimental determinations of the strength and stiffness of wood as influenced by moisture have been made in the laboratories of the U. S. Forest Service and are reported in Bulletin 70 and Circular 108. While these investigations have not covered all of our important timber woods, much important information has been derived from them. The woods studied were long-leaf pine, red spruce, chestnut, loblolly pine, Douglas fir, tamarack, and Norway pine. In the cases of the first three of the above varieties the study covered the effect of moisture upon compressive strength along the grain, strength (modulus of rupture) in bending, and strength in shearing along the grain, also stiffness (modulus of elasticity) in compression and in bending. For the remaining varieties only the effect of moisture upon compressive strength along the grain has been studied.

From the facts observed in this series of tests the following conclusions may be drawn:

(1) *Compressive Strength Parallel to the Grain.*

(*a*) Loss of moisture does not affect strength, Fig. 341, or stiffness, Fig. 342, in any way until the total moisture content has been

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* U. S. Forest Service, Circular 108.

reduced below the critical percentage which represents the fiber-saturation point.

(*b*) The fiber-saturation point having been passed, the rate of gain in strength and stiffness varies considerably for different woods, always becoming greater as the total moisture decreases.

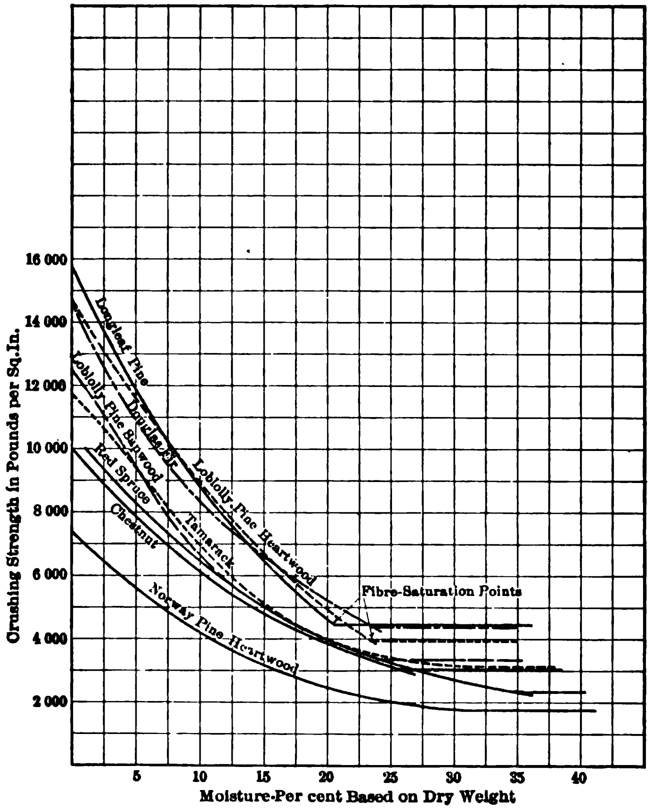

FIG. 341.—Relation between Strength in Compression Parallel to the Grain and Moisture Content for Several Woods. (Cir. 108, U. S. For. Ser.)

(*c*) The green strength of the woods tested amounted, as a rule, to from 50 to 60 per cent of the strength in the normal air-dry condition (12 per cent moisture); and the strength of the kiln-dry wood (3.5 per cent moisture), exceeded the strength of the air-dry woods by from 50 to 70 per cent. The actual numerical relations found in the tests were as follows:

Wood.	Ratio of Strength, Green, to Strength Air-dry.	Ratio of Strength, Kiln-dry to Strength Air-dry.
Long-leaf pine	.58	1.67
Red spruce	.41	1.53
Chestnut	.55	1.55
Loblolly pine (heartwood)	.50	1.56
Loblolly pine (sapwood)	.59	1.78
Douglas fir	.59	1.55
Tamarack	.51	1.63
Norway pine	.49	1.66

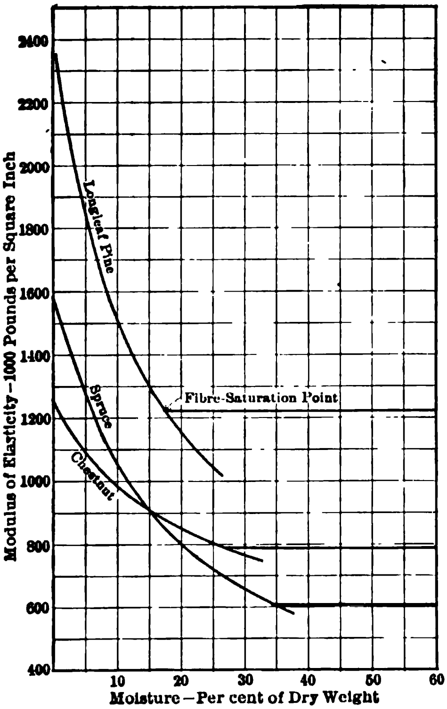

FIG. 342.—Variation of Stiffness in Compression Parallel to the Grain with Moisture Content. (Cir. 108, U. S. For. Ser.)

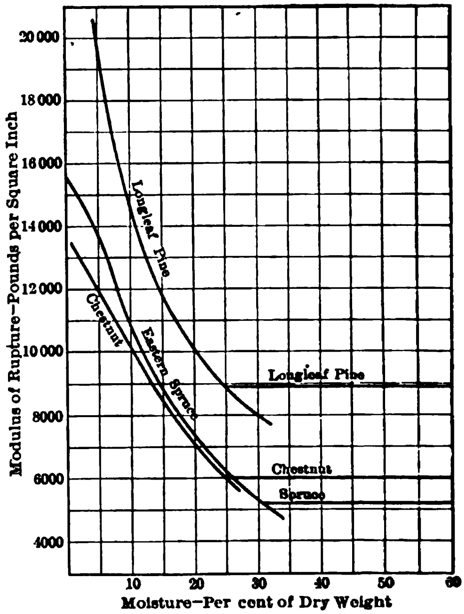

FIG. 343.—Variation of Strength in Bending with Moisture Content. (Bull. 70, U. S. For. Ser.)

(2) *Strength in Bending. Modulus of Rupture.*

(*a*) Same as (*a*) above, Fig. 343.

(*b*) Same as (*b*) above.

(*c*) The modulus of rupture of green woods of the varieties tested amounted to from 50 to 70 per cent of the value found for the same woods when air-dry, and the modulus of rupture of kiln-dry woods exceeded the value found for the same woods when air-dry by from 33 to 65 per cent. The numerical relations established were as follows:

Wood.	Ratio of Mod. of Rupt., Green, to M. of R., Air-dry.	Ratio of Mod. of Rupt., Kiln-dry, to M. of R., Air-dry.
Long-leaf pine	.67	1.65
Red spruce	.52	1.45
Chestnut	.65	1.33

(3) *Stiffness in Bending. Modulus of Elasticity.*

(*a*) Same as (*a*) above, Fig. 344.

(*b*) Same as (*b*) above. Effect of moisture is not nearly so marked in case of stiffness as in case of either compressive or bending strength.

(*c*) The modulus of elasticity of green woods of the varieties tested amounted to from 80 to 84 per cent of the value found for the same wood when air-dry, and the modulus of elasticity of kiln-dry woods exceeded the value found for the same woods when air-dry by from 14 to 34 per cent. The numerical relations established were as follows:

Wood.	Ratio of *E*, Green, to *E*, Air-dry.	Ratio of *E*, Kiln-dry, to *E*, Air-dry.
Long-leaf pine	.84	1.34
Red spruce	.80	1.14
Chestnut	.84	1.21

579. Weight and Strength. It has long been known that the strength of a given species of wood is directly dependent upon the dry weight (specific gravity). Tests of the U. S. Forest Service made in 1896 * indicated further that this law of variation holds good not only for a given species, but irrespective of species for the four principal pines of our Southern States. In 1897, further tests † indicated that the application of the law might be extended further, and it was cautiously stated as a probability that " in woods of uniform structure strength increases with specific weight, independently of species and genus distinction, i.e., other things being equal, the heavier wood is the stronger." The relation indicated between weight and compressive strength parallel

* Circular 12.

† Circular 15.

with the grain was expressed by a single rule which agreed approximately with the observed results in tests of most classes of timber, except the oaks, which apparently follow a somewhat different law, the strength corresponding to a given weight being considerably lower than in case of other woods.

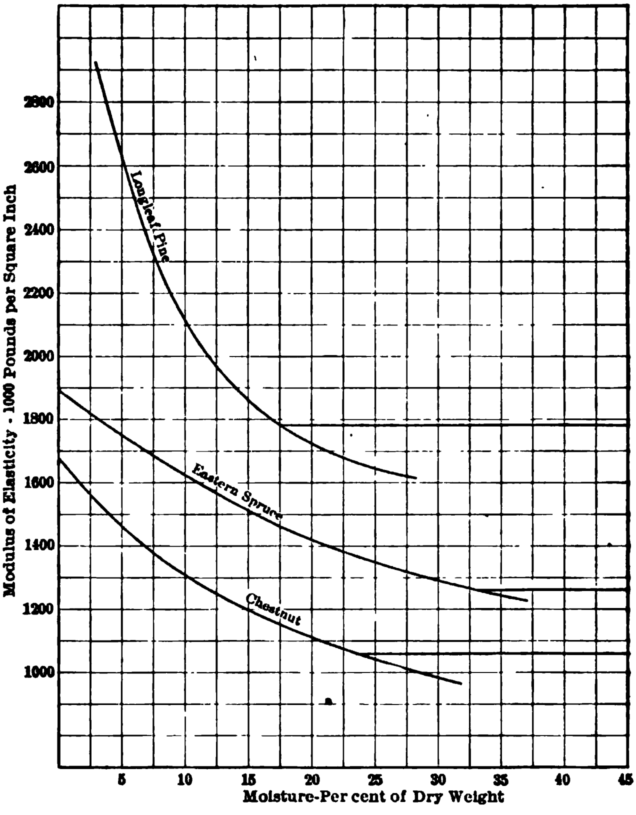

Fig. 344.—Relation between Stiffness in Bending (Modulus of Elasticity) and Moisture Content for Three Species. (Cir. 108, U. S. For. Ser.)

More extensive tests, carried out later in a more careful manner, have tended to qualify the original general conclusions, and it has been repeatedly brought out in the analysis of tests of the Forest Service that, while the mechanical properties of wood vary directly with its dry weight for a given species, the relation is far from being constant in all species.

Bulletin 108 of the Forest Service gives detailed information on the subject so far as most of the conifers are concerned. Reliable information is not yet obtainable concerning the broad-leaved woods.

The curves of Fig. 345 express the relation between dry weight and bending strength (modulus of rupture) and stiffness (modulus of elasticity) of small clear beams.

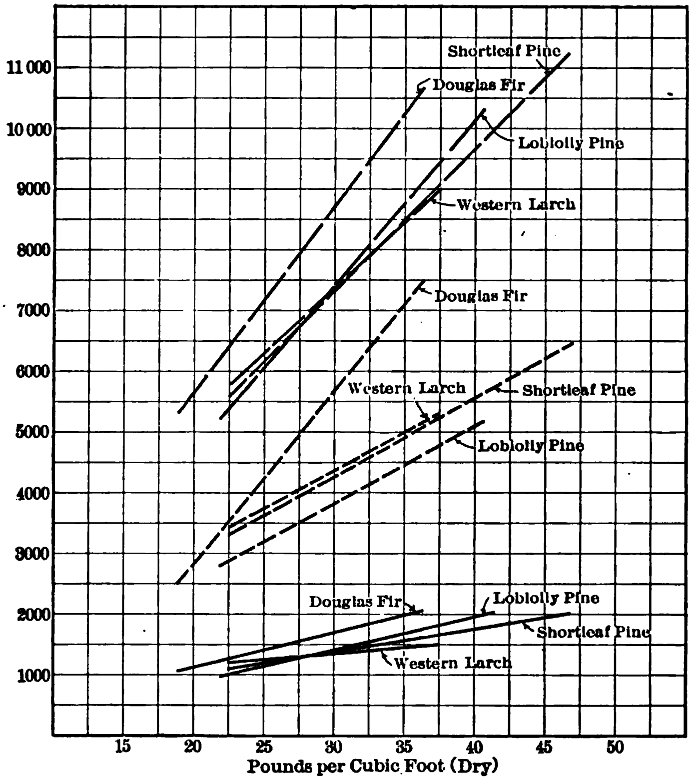

FIG. 345a.—Relation of Strength and Stiffness of Conifers in Bending to Dry Weight. (Bull. 108, U. S. For. Ser.)

Since the position of a specimen in the log (height or position in the section), influences the density of the wood, the influence of this factor is covered in the above discussion.

580. Rate of Growth, Proportion of Summer Wood, and Strength. The average rate of growth of timber is readily computed by counting the annual rings along a radial line and dividing by the length of the line. The relation between rate of growth and bending strength for the timbers considered in the preceding article was also investigated and reported upon in Bulletin 108 of the Forest Service. The indications from these studies were that for most species there is a rate of growth

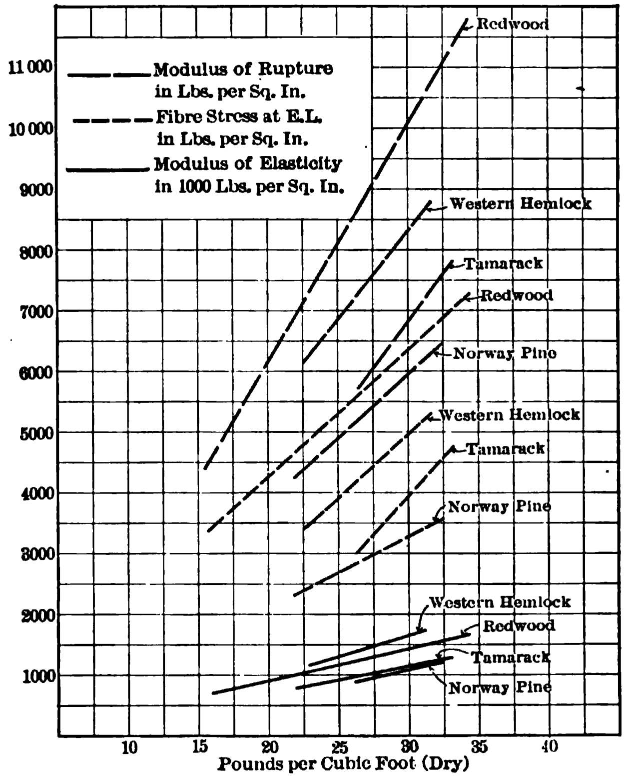

FIG. 345b.—Relation of Strength and Stiffness of Conifers in Bending to Dry Weight. (Bull. 108, U. S. For. Ser.)

which, in a very general way, is associated with the greatest strength. For the species tested this appeared to be as follows:

	Rings per inch.
Douglas fir	24
Short-leaf pine	12
Loblolly pine	6
Western hemlock	18
Tamarack	20
Norway pine	18
Redwood	30

It was found, however, that the variation between different individuals of a species was very great, so that, although an effort was made to express the average relation between rate of growth and strength for each species, no great reliance could be placed upon the average relation so determined, and the conclusion was stated " that rings per inch are not a reliable index to the mechanical properties of timber, especially structural timbers containing knots and other defects."

The proportion of summer wood in the section of a timber of any species is closely related to the dry weight. It is therefore to be expected that the relation between the proportion of summer wood and strength should agree closely with the relation between dry weight and strength. The studies of the Forest Service show well the identity of these two relations as factors influencing strength, and the proportion of summer wood is therefore an important guide in judging the quality of timber.

581. The Time Factor in Tests of Timber. Timber differs from most other materials in that small variations in the rate of application of load have a more pronounced effect upon the strength and stiffness shown by a specimen under test. If a timber-compression block or beam is loaded rapidly, it will appear to have a higher elastic limit and ultimate strength, and will also appear to be stiffer, than it will if it is loaded less rapidly. This behavior is due to the fact that the deformation lags far behind the load, and if any load is permitted to remain upon a specimen for a sensible time interval the deformation increases, the amount of increase becoming greater for heavier loads. Actual failure appears to be consequent upon the attainment of a certain limiting amount of deformation or strain, rather than a limiting load or stress. This condition of affairs makes it necessary to standardize tests by adopting certain speeds of loading for each class of specimens, or, rather, to so proportion the speed of the moving head of the testing machine to the dimensions of the specimen that the resultant rate of fiber strain will be a certain specified amount. The usual practice is to adhere to the standards established by the Forest Service for the use of engineers of timber tests. These standards are as follows: *

Character of Tests.	Character of Specimens.	Rate of Fiber Strain in Ins. per Minute.
Bending tests	Timber of structural sizes	0.0007
Bending tests	Small test specimens	0.0015
Compression with grain	Timber of structural sizes	0.0015
Compression with grain	Small test specimens	0.0030
Compression across grain	Timber of structural sizes	0.0070
Compression across grain	Small test specimens	0.0150

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* " Instructions to Engineers of Timber Tests," Cir. 38 (revised), U. S. Forest Service.

When constant loads amounting to a large fraction of the ultimate strength of timber are sustained for very long periods, the deformation may continue to increase until rupture occurs, even though the stress encountered is far below the ultimate strength of the timber as originally determined. A number of series of long-time tests have shown that for timbers loaded either transversely or in compression with loads amounting to from 50 to 60 per cent of the ultimate strength usually found, failure will ultimately occur, the time required varying from a few weeks to several months.

This important conclusion may therefore be drawn: "The strength of timber under any kind of permanent load is only about one-half its strength as found by actual (short-time) tests." *

582. Tabulation of Mechanical Properties of Structural Timbers. The following tabulation of the mechanical properties of American timber has been compiled from the tests of the U. S. Forest Service. Table I is a summary of tests of forty-nine species of wood tested in a green condition (Circular 213), and Table II is a summary of tests of thirty-two species of wood, all values being obtained with—or reduced to—12 per cent moisture (Circular 15). Small clear-test specimens were used in all of the tests.

583. Factor of Safety and Working Stresses. The factor of safety used in the design of timber structures is a very variable quantity. Merriman † gives 8 for steady stress, 10 for varying stress, and 15 for shocks; Rankin ‡ gives 4 to 5 for dead load and 5 to 10 for live load; and the Cambria Steel Co. Handbook gives 10 for tension, 6 for extreme fiber stress in bending, 5 in compression along the grain, and 4 for compression across the grain and for shear. The variability of the factors given by different authorities indicates that the factor of safety for timber is in a large measure an expression of ignorance or lack of confidence in the reliability of values of strength upon which designing is based.

As an example of the best current practice the following table of safe working stresses recommended in 1909 by the Committee on Wooden Bridges and Trestles of the American Railway Engineering Association is given. In comparing these figures with those given above, account must be taken of the fact that the present figures apply to green timbers (all large timbers must always be assumed to be no stronger than green timber) of structural sizes used for railway bridges and trestles where always subjected to vibration and shock. The committee recommends that these values be increased 25 per cent for highway bridges, and 50

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* Johnson, "Materials of Construction," p. 468*b*.

† "Mechanics of Materials."

‡ Civil Engineer's Handbook.

RES[illegible]S

Number of trees.	…parallel to …n. Ri… p… in… h	…parallel to …n. Modulus of elasticity.	Compression perpendicular to grain, fiber stress at elastic limit.	Hardness—Load required to embed a 0.444-in. ball to ½ its diameter. End surface.	Hardness—Radial surface.	Hardness—Tangential surface.	Shearing strength parallel to grain. When surface of failure is Radial.	Shearing strength—Tangential	Cleavage strength per in. of width. Radial.	Cleavage—Tangential	Tension perpendicular to grain. Radial.	Tension—Tangential
	…r	1000 lbs. sq.in.	Lbs. per sq.in.	Lbs.	Lbs.	Lbs.	lbs. per sq.in.	lbs. per sq.in.	Lbs.	Lbs.	lbs. per sq.in.	lbs. per sq.in.
.....	23	......	452	565	542	546	876	832	275	260	......	......
5	14	1531	889	1121	1000	1017	1360	1312	333	346	645	671
5	20	1497	801	842	729	734	1239	1166	357	341	616	611
3	23	1016	197	273	226	217	560	617	130	168	226	303
5	1[illegible]	1412	605	1012	897	918	1154	1375	339	527	633	969
5	1[illegible]	1915	439	827	768	739	1103	1188	294	287	446	526
.....	30	......	696	954	883	893	1210	1330	282	377	......	......
1	8	1453	730	919	757	687	1197	1174	401	424	765	832
.....	19	......	292	536	456	497	778	872	210	270	......	......
20	...	......	......	......	......	......	......	......	......	......	......	......
1	8	1068	575	829	795	773	1095	1161	422	436	661	786
10	23	1658	994	......	......	......	1134	1191	......	......	......	......
9	13	1257	1000	......	......	......	1094	1330	......	......	......	......
11	11	1616	986	......	......	......	1134	1348	......	......	......	......
8	19	1681	1065	......	......	......	1165	1375	......	......	......	......
11	16	1359	958	......	......	......	1251	1313	......	......	......	......
1	31	1904	......	......	......	......	......	......	......	......	......	......
5	22	1411	938	......	......	......	1010	1053	......	......	......	......
4	17	1474	1101	......	......	......	1200	1215	......	......	......	......
10	18	1681	1224	......	......	......	1235	1620	......	......	......	......
27	18	1911	1130	......	......	......	1312	1405	......	......	......	......
19	22	1980	1114	......	......	......	1334	1457	......	......	......	......
4	20	1869	1158	......	......	......	1206	1318	......	......	......	......
9	17	1478	1080	......	......	......	1337	1505	......	......	......	......
1	24	1029	......	......	......	......	......	1245	......	......	......	......
10	19	1943	972	......	......	......	1230	1297	......	......	......	......
2	15	1926	1088	......	......	......	1390	1490	......	......	......	......
1	3	1536	1684	1862	1860	1832	1885	2096	552	610	1133	1445
.....	20	......	606	766	621	626	1130	1330	297	330	......	......
5	19	1463	653	992	918	901	1193	1455	376	513	610	864
.....	22	......	870	965	815	815	1340	1530	357	451	......	......
5	30	1062	1148	1139	1068	1081	1196	1402	354	487	714	924
5	11	1335	844	1139	1044	1039	1215	1226	367	446	659	880
6	1	1295	807	1107	1020	1002	1132	1195	380	470	639	874
5	1	1924	682	924	884	901	1047	1059	365	410	683	787
1	1	1489	943	1205	1217	1099	1198	1394	428	536	757	909
.....		......	1355	......	......	......	1414	1414	......	......	......	......
5	2	946	829	1113	1030	943	1096	1292	382	457	622	749
5	1	1308	727	1087	1049	1047	1187	1425	342	506	632	997
5	1	1181	1004	1183	1163	1147	1138	1368	371	474	624	986
5	1	1465	912	1093	1083	1031	1162	1196	379	470	728	929
.....	1	......	802	847	800	790	1270	1320	337	365	......	......
1		1331	2260	1838	2312	1762	......	......	......	......	......	......
5	1	1073	433	664	560	599	900	1102	265	425	540	781
1	1	1280	451	814	660	733	978	1084	277	380	472	796
5	2	754	288	321	225	228	617	614	148	139	241	235
9	1	868	518	......	......	......	613	662	......	......	......	......
4	2	1738	548	460	355	354	836	800	167	154	242	251
5	1	882	307	284	203	235	573	654	130	133	......	......
14		1579	334	......	......	......	517	639	......	......	......	......
5	1	1440	427	415	399	416	853	858	139	127	......	......
5		1332	445	381	322	334	742	723	145	187	213	304
5	2	1054	420	463	354	334	790	813	168	151	271	323
5	2	1219	364	288	307	316	672	747	142	140	......	......
5	3	991	332	316	318	319	709	719	253	200	......	......
5	1	1890	491	574	502	521	1060	953	187	180	240	298
5	2	1646	358	355	345	340	812	741	161	154	179	205
70	1	......	400	......	......	......	746	670	......	......	......	......
5	1	1029	353	334	307	342	702	714	168	189	239	304
5	2	1046	342	310	311	318	644	680	152	179	281	321
5	1	1271	326	316	306	323	686	706	162	187	230	252
5	3	1174	410	315	330	332	694	717	152	154	......	......
5	1	1318	314	304	294	299	649	639	144	160	225	285
.....	1	1175	539	......	......	......	......	......	......	......	......	......
.....	2	1272	618	......	......	......	......	......	......	......	......	......
5	1	1021	302	272	253	274	607	624	110	135	......	......
5	1	971	279	231	216	226	538	600	129	143	......	......
4	2	......	322	......	......	......	754	783	......	......	......	......
2		......	262	......	......	......	645	615	......	......	......	......
5	1	1596	480	401	380	370	883	843	167	159	236	274

TABLE II

MECHANICAL PROPERTIES OF 32 SPECIES OF AMERICAN WOODS

(ALL VALUES REDUCED TO 12 PER CENT MOISTURE.) (SMALL SPECIMENS USED.)

(U.S. Forest Service Circular 15)

Species Common Name.	No. of Tests.	Sp.gr.	Strength in Pounds per Square Inch.					
			Cross-bending.			Compression along Grain.	Compression across Grain.	Shearing along Grain.
			Apparent Elastic Limit.	Mod. of Rupt.	Mod. of Elas. ÷ 1000.			
Pignut hickory	30	.89	12,600	18,700	2730	10,900	3200	1200
Mockernut hickory	75	.85	11,700	15,200	2320	10,100	3100	1100
Bitternut hickory	25	.77	11,100	15,000	2280	9,600	2200	1000
Shagbark hickory	137	.81	11,200	16,000	2390	9,500	2700	1100
Pecan hickory	37	.78	11,600	15,300	2530	9,100	2800	1200
Nutmeg hickory	72	.78	9,300	12,500	1940	8,800	2700	1100
Cuban pine	410	.63	11,100	13,600	2370	8,700	1200	770
White oak	218	.80	9,600	13,100	2090	8,500	2200	1000
Water hickory	14	.73	9,800	12,500	2080	8,400	2400	1000
Texan oak	117	.73	9,400	13,100	1860	8,100	2000	900
Cedar elm	44	.74	8,000	13,500	1700	8,000	2100	1300
Green ash	10	.62	8,900	11,600	2050	8,000	1700	1000
Long-leaf pine	1230	.61	10,000	12,600	2070	8,000	1260	835
Water oak	31	.73	8,800	12,400	2000	7,800	2000	1100
Spanish oak	251	.73	8,600	12,000	1930	7,700	1800	900
Cow oak	256	.74	7,600	11,500	1610	7,400	1900	900
Loblolly pine	660	.53	9,200	11,300	2050	7,400	1150	800
Overcup oak	216	.74	7,500	11,300	1620	7,300	1900	1000
Yellow oak	40	.72	8,100	10,800	1740	7,300	1800	1100
Spruce pine	170	.62	8,400	10,000	1640	7,300	1200	800
Red oak	57	.72	9,200	11,400	1970	7,200	2300	1100
Willow oak	153	.72	7,400	10,400	1750	7,200	2300	900
White ash	87	.62	7,900	10,800	1640	7,200	1900	1100
Post oak	49	.80	8,400	12,300	2030	7,100	3000	1100
Sweet gum	118	.59	7,800	9,500	1700	7,100	1400	800
Red pine	100	.50	7,700	9,100	1620	6,700	1000	500
White elm	18	.54	7,300	10,300	1540	6,500	1200	800
Short-leaf pine	330	.57	7,800	10,100	1680	6,500	1050	770
Bald cypress	655	.46	6,600	7,900	1290	6,000	800	500
Douglas spruce	41	.51	6,400	7,900	1680	5,700	800	500
White pine	130	.38	6,400	7,900	1390	5,400	700	400
White cedar	87	.37	5,800	6,300	910	5,200	700	400

per cent for buildings and similar structures wherein the timbers are protected from the weather and are not subject to impact. The committee has used the following factors of safety: viz., 5 for extreme fiber stress in bending, 4 for shear along the grain, 3 for compression along the grain, and 2 for compression across the grain. For steady loads these factors become 3⅓, 2⅔, 2, and 1⅓ respectively.

SAFE WORKING STRESSES FOR STRUCTURAL TIMBER

(Adopted by Am. Ry. Eng. Assn., 1909)

(All values expressed in pounds per square inch)

Kind of Timber.	Compression.		Bending Extreme Fiber Stress.	Shearing along Grain.
	Along Grain.	Across Grain.		
Douglas fir	1200	310	1200	170
Long-leaf pine	1300	260	1300	180
Short-leaf pine	1100	170	1100	170
White pine	1000	150	900	100
Spruce	1100	180	1000	150
Norway pine	800	150	800	130
Tamarack	1000	220	900	170
Western hemlock	1200	220	1100	160
Redwood	900	150	900	80
Bald cypress	1100	170	900	120
Red cedar	900	230	800	
White oak	1300	450	1100	210

In using above values do not increase the live-load stresses to take account of impact.

DURABILITY, DECAY, AND PRESERVATION OF TIMBER

584. Durability and Decay of Timber.* "The decay of wood is not an inorganic process like rusting of iron or the crumbling of stone, but is due to the activities of low forms of plant life called bacteria and fungi." Bacteria are among the lowest forms of life, often only a single cell which multiplies by division into two cells which in turn divide again. Several such cells united together form a thread or filament of microscopic size. Fungi consist merely of tiny threads, known as mycelium, which in most of the higher forms grow together to form compact masses as, for instance, the toadstools which grow on rotting logs and the "punks" or "brackets" on the trunks of forest trees. The action of fungi and bacteria in destroying wood is, so far as is known, about the same, and the two will therefore be considered together.

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* Bulletin 78, U. S. Forest Service.

The mycelium starts from a single spore (a primitive substitute for seed, which are born in infinite numbers by the fruiting fungi, and are distributed by the wind). Under favorable conditions the spore sprouts or germinates, sending forth a single thread or hypha which branches and rebranches quickly. The hyphæ creep through the tissues of the material in which they are growing and absorb the materials necessary for their growth. In living cells they attack the protoplastic contents —the starches, sugars, and oils. In dead cells they attack the cell walls. After a time some hyphæ form the fruiting body which bears a crop of spores. The action of the fungi results in complete or partial solution of the substance attacked. The sugars may be absorbed by the fungus directly or changed to a more easily digested sugar, the starches are changed to sugar and then absorbed. The nitrogenous substances undergo similar changes. Wood fibers may be dissolved entirely, or only the cellulose or lignin elements may be affected. The chemical changes bring about physical changes, the hard elastic fibers becoming a mushy mass or a dry brittle substance which falls to pieces at the least touch. At first the hyphæ simply puncture the cell walls here and there, later they increase in number until the strength of the wood is lost entirely. The solvent action of the ferments of the fungi upon the cellulose or wood fiber often causes cracks, while other ferments dissolve the tissue in the intercellular spaces so that the cells ultimately fall apart. Some fungi require oxygen, and others grow best without; some require sugar and starches, while others do not; all require some moisture.

Susceptibility to decay and comparative resistance to decay vary with different classes of timber. The determining factors are as yet almost unknown. Hardness, density, specific gravity, and strength seem to have no influence one way or the other. Some very hard tropical timbers decay very rapidly while others last very long. Hard strong oak decays much faster than light porous cypress; tamarack and hemlock decay rapidly, while cypress and cedar are lasting; elm and birch are short lived, the locust long lived, etc.

585. The Preservation of Timber. The simplest way to prolong the life of timber exposed to the attack of fungi is to reduce the moisture content by seasoning. By piling timber so as to permit free access to air all around it, the moisture may be reduced to about 15 to 18 per cent. Of course the climate and the size of the timbers have a great influence upon the rate of seasoning and the total amount of moisture lost.

The moisture content of air-dry wood may be still further reduced by kiln drying, but the effectiveness of all methods of moisture reduction as a preservative measure must be limited by the fact that timber so dried readily reabsorbs moisture upon being again exposed to dampness, and and benefits obtained are only moderate.

" By far the best method of checking the growth of fungi, however, is by poisoning their food supply—by injecting poisonous substances into the timber, so changing the organic matter into powerful fungicides." It is a widespread idea that the germs of decay are inherent in the wood, needing only an opportunity for development to bring about its destruction. On the contrary, all wood-destroying agencies start from the outside and may even be excluded by certain paints which merely coat the surface of the timber but which are poisonous enough to prevent the germination of spores. "The ancients were in the habit of painting their statues with oily and bituminous preparations to preserve them from decay. The great wooden statue of Diana at Ephesus, which was supposed to have descended miraculously from heaven, was protected from earthly decay by oil of nard. When the preservative fluids were extracted from the heart of an Egyptian mummy that had resisted decay for over 3000 years, decomposition immediately set in. This showed that it was the presence of the antiseptic which prevented decay, and not a chemical change of the tissues."

The first deliberate attempts to preserve timber from decay date back many centuries, when wood was charred to make it more resistant. Later came the period when wood was coated with preservative paints, then came attempts to inject preservatives into the wood.

" Of the many antiseptics which have been proposed for the preservation of timber only four have been largely used with success in the United States. These are *creosotes* (dead oil of coal tar), *zinc chloride*, *corrosive sublimate* (bichloride of mercury), and *copper sulphate*. At the present time copper sulphate has fallen into almost total disuse, and corrosive sublimate is restricted to two plants in New England." There are many patented preservatives known by various names, practically all of which have either creosote or zinc chloride as their base.

Creosote is a by-product of coal tar produced at illuminating gas plants and by-product coke oven plants. Creosote is not a simple substance like zinc chloride, but is a complex compound of phenols (tar acids), naphthalene, anthracene, and residues. *Wood creosote*, distilled like coal tar from wood, also possesses strong antiseptic properties. *Zinc chloride* is obtained by dissolving metallic zinc in hydrochloric acid. This is diluted with water before being used as a wood preservative. Creosote has the advantage of insolubility in water, so that it will not wash out of timber; zinc chloride has the advantage of much greater cheapness, and so is preferred for use in comparatively dry situations.

The processes by which preservatives are injected into timber may be divided into two general classes, the " pressure processes " and the " non-pressure processes," the distinction being only in the fact that in the former force pumps, air compressors, etc., are utilized, while in the latter only atmospheric pressure is relied on.

The Pressure Processes

The Breant Process. One of the earliest practical pressure processes was that devised by Breant in France in 1831. The timber is inserted in a vertical cylinder and the liquid forced in almost to the top. A vacuum is produced by opening a connecting valve to an auxiliary chamber which has been exhausted by an air pump, after which the valve is closed and the liquid forced in till a pressure of 10 atmospheres is reached. The time required for impregnation is about six hours.

The Bethall process, a modification of the Breant process, using creosote, and the process of *Burnettizing,* using zinc chloride, are the most widely used pressure processes. The method of injection is practically the same for each. The timber to be treated is placed on iron trucks or " cylinder buggies " and run into huge horizontal cylinders 8 or 9 feet in diameter and often as much as 150 feet long, after which the doors are hermetically sealed. Live steam is admitted at a pressure of 20 pounds per square inch for several hours, then the steam is blown out, the vacuum pump started, and within a few hours as much air and moisture as possible are exhausted. Finally, the preservative is run into the cylinder at a temperature of about 160° F., the pressure pumps are started, and the desired amount of preservative is forced into the timber. The surplus preservative is now blown back into the tank, the timber allowed to drip for a few moments, and then withdrawn.

The boiling process is used principally for Douglas fir on the Pacific coast. The timber is placed in the cylinder, which is filled with creosote slightly above the boiling-point of water, and kept in this condition for a period of from a few hours to two days, during which time water and volatile oils are driven off. Finally a pressure of 100 to 125 pounds per square inch is applied and the temperature is allowed to drop, thus forcing the preservative into the timber.

In the *A. C. W. process* the procedure is like that of the Bethall except that air pressure (15 pounds per square inch) is applied after the vacuum, and maintained while the creosote is admitted in order to prevent unequal absorption during the filling of the cylinder. Then 100 pounds per square inch pressure is applied till the penetration reaches the desired degree, after which the preservative is drawn off and air forced in at a pressure of 60 to 80 pounds per square inch to increase the penetration of the preservative.

The Rüping process is largely used with creosote, and is the best known *empty-cell* process. The timber is air-dried before being placed in a cylinder. Air is forced in at 75 pounds per square inch pressure till the wood is filled with the compressed air. Then, without abating the pressure, the oil is admitted at a higher pressure (80 to 85 pounds per square inch). The pressure is subsequently increased to 225 pounds per square inch. This forces the penetration of the oil into the timber. Finally the valves are opened, the excess oil is drawn off, so relieving the pressure around the timber, and the expansive force of the compressed air in the wood forces out much of the oil, leaving only a coating around the cell walls, thus resulting in a deep penetration with a light absorption.

The Lowry process tries to accomplish the same effect without using compressed air. The air-seasoned timber is introduced into the cylinder, oil is admitted, and a great pressure applied, causing a compression of the air in the wood cells and intercellular space. Finally the oil is withdrawn, a strong vacuum is formed and the expanding of the compressed air forces out the oil as in the Rüping process.

The creo-resinate process consists in impregnating the timber with a mixture of creosote and resin (50 to 75 per cent creosote). The method differs from the Bethall process only in using dry heat instead of a steam bath before the vacuum.

The Wellhouse process is an attempt to prevent the leaching out of zinc chloride from treated timber. It relies for its efficiency upon the tendency of glue and tannin, when combined, to form a leathery, waterproof substance, or "leatheroid." A ½ per cent solution of glue is mixed with the zinc chloride solution and forced into the timber, and a tannin solution is afterward forced in. The formation of "leatheroid" in the cell openings tends to prevent the absorption of water and the leaching out of the salt.

The Allardyce process is an attempt to devise a process cheaper than one using creosote and not involving the leaching out of zinc chloride. Zinc chloride in a 2 or 3 per cent solution is first forced into the timber (12 pounds per cubic foot) by a process similar to "Burnettizing" and then creosote is injected (3 pounds per cubic foot of timber). The creosote remains largely on the exterior and is designed to protect the soluble chloride in the interior.

The card process is a similar one in its objects. The preserving fluid contains 15 to 20 per cent of creosote, and a 3 to 5 per cent solution of zinc chloride for the remainder. After a steam bath and vacuum the preservative is admitted under pressure. The two preservatives will not mix, and are of different specific gravity, so they are kept in a mechanical mixture by a centrifugal force pump which draws the solution from the top and forces it back through perforated pipes running along the bottom of the cylinder.

The Non-pressure Processes

Injection of preservatives by the non-pressure processes depends on different principles from those involved in the pressure processes. The wood, after being seasoned in air, is immersed in a bath of hot liquid in a suitable containing vessel for from one to six hours, during which time the air and moisture in the wood expand and partially pass off. Then, as quickly as possible, the wood is changed to a bath of cooler preservative. This causes contraction of the imprisoned air and moisture, creating a partial vacuum which is subsequently destroyed by the entrance of the preservative. *Green-timber processes* prolong the hot bath until much of the moisture in the green wood has been expelled. Air is not present to help in forming a vacuum, so the treatment is slow and unsatisfactory, as well as expensive, through loss of time and evaporation of the preservatives.

The oven process is founded upon the fact that the hot bath serves only to expand the air and moisture, and drive them out, with practically no penetration of the preservatives until the cold bath is reached. Much the same results may sometimes be secured by subjecting the timber to dry heat in an oven or kiln and then immersing quickly in a bath of cold preservative. Only in special cases is the process desirable, as when a metal-corroding preservative is used and metal tanks and steam coils cannot be employed, in which case the dry hot timber is plunged into a cold bath in a wooden tank.

The Empty Cell Non-pressure Process

In the non-pressure processes empty cells cannot be secured by vacuum, force pumps, etc., so that the problem of securing a good penetration with a small quantity of preservative used presents itself. But here again the non-pressure processes have proven successful, and for some of the more porous woods the depth of penetration and the economy of preservative compares favorably with empty-cell processes in pressure treatments.

Practically the only difference in this process from the usual non-pressure process is that here the length of time of immersion in the cold bath is shortened. Suppose that the hot bath has partially expelled the air and moisture to a depth of 3 inches in a timber. When the cold bath is applied the drop in temperature first takes place in the outer band of wood, causing the partial vacuum to first form there. This causes an inrush of the preservative which fills the intercellular and cellular space. If the timber is withdrawn before the preservative has penetrated more than 2 inches, instead of the 3 inches affected by the hot bath, the subsequent cooling of the third inch causes a further vacuum to form, and subsequently be destroyed by the admission of superfluous oil from the outer saturated portion, thus resulting in a depth of penetration of 3 inches with the amount of preservative required to saturate 2 inches. A second hot bath is sometimes employed with similar results. The oil is a better heat conductor than the wood, causing a further heating of the interior, resulting in second expansion and expulsion of air and moisture, with the formation of a partial vacuum which is destroyed by the increased penetration of the excess oil in the outer portion when the stick is exposed in air.

The low-pressure process, developed by the Forest Service, consists in subjecting the seasoned timber first to a hot bath to cause expansion and expulsion of air and moisture followed by a cold bath. In this latter bath atmospheric pressure is not depended upon, but low pressure, not exceeding 70 pounds per square inch, is applied by means of the pumps which force in the preservative. The treatment is carried out in cylinders as in ordinary pressure processes.

The non-pressure processes and the low-pressure processes can be used only in a restricted field. They are not adapted to use with non-porous woods or where large quantities of timber must be treated in a short time.

Superficial Treatments

Less efficient but cheaper treatment can be secured by painting the face of the timber with at least two coats of hot creosote or some similar preservative (the *brush method*). The liquid will not penetrate to any great extent, but as long as there remains an unbroken antiseptic zone around the surface the spores of the fungi cannot enter. Thorough air-seasoning before painting is necessary, since otherwise checks may form and provide a means of access to the interior of the timber for the spores of the fungi.

A still less expensive treatment than the brush treatment is the method of dipping the timber in an open vat of the preservative. Usually the timbers are carried through the bath on chain conveyors and remain submerged only a few minutes at most. *Dipping* is not only more economical of time and labor, but gives better results than the brush method.

Effect of Preservative Treatments upon Strength of Timber

The effect of preservative treatments of timber upon strength has been investigated by the Forest Service under the charge of Professor W. K. Hatt,* Fig. 346. It appears in general that the strength of treated timber depends, first, on the percentage of moisture remaining in the wood, and second, on whether the wood has been subjected to injuriously high temperatures during the process of steaming and the vacuum treatment. A high degree of steaming is injurious to wood, the limit of safety depending upon the quality of the wood, the degree of seasoning, and the temperature and duration of the steam bath. For loblolly pine this limit was found to be 30 pounds per square inch for four hours or 20 pounds per square inch for six hours. During steaming the amount of moisture in the wood must be increased with consequent weakening of the fibers if the vacuum following the steam is not able to remove the added moisture. There seems to be no ground for believing that non-pressure processes can be injurious to the strength of the timber.

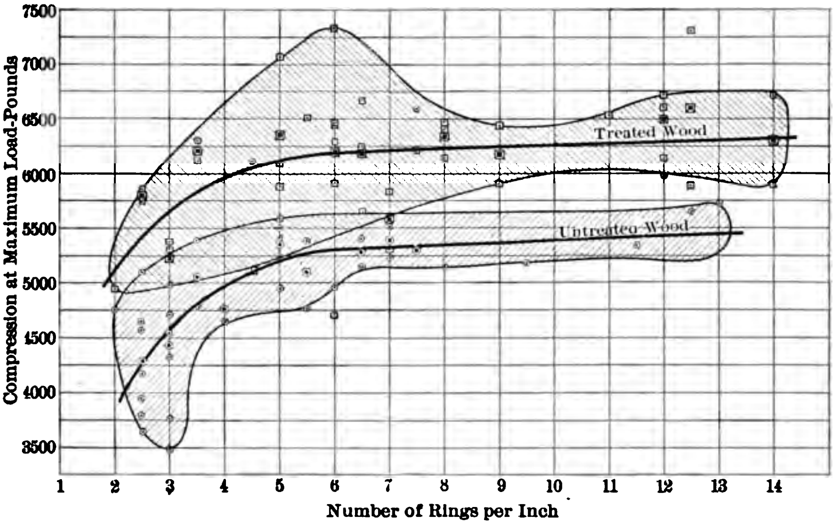

FIG 346.—Comparative Strength of Loblolly Pine Untreated and Creosoted without Steaming. (Cir. 39, U. S. For. Ser.)

The presence of creosote in itself will not weaken wood, since it appears not to enter the cell walls and fibers, but only to coat them,

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* Circular 39, U. S. Forest Service.

and so, if the wood is not perfectly seasoned, the temperature of the bath may aid the seasoning and increase the strength of the wood.

The presence of zinc chloride will not weaken wood except by the addition of water by reason of the fact that it is in itself a water solution. Subsequent seasoning will obviate this difficulty. A too-concentrated solution may cause chemical dissolution of some of the wood fibers, but this danger can easily be avoided.

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